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DISCOMFORT GLARE IN LIGHTED STREETS

By R. G. HOPKINSON, B.Sc.(Eng.), F.R.P.S.

(Communication from the Staff of the Research Laboratories of The General Electric Company Limited, Wembley, England.)

(Paper read on Tuesday, January 9th, 1940.)

SUMMARY.

Glare which affects comfort or causes distraction is distinguished from glare which affects the ability to see. The results of an investigation to determine the factors which cause discomfort glare in lighted streets are summarised, and the influence of these factors on problems of street lighting design is studied.

Discomfort glare was found to be influenced by the general brightness of the scene, by the angle between the direction of a glare source with the line of sight, and, under street lighting conditions, by both the intensity and intrinsic brightness of the source. The glaring effects of a number of sources were found to be additive. No difference in the glaring effects of yellowish, bluish, and white light could be detected.

It has been found possible to express the results in a form easily applicable to problems of street lighting design.

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I. Discomfort glare calculations.
II. Measurement of the intensities of the glare sources of an installation.
III. Measurement of θ, the angle of separation of a glare source from the line of sight.

1. Introduction—Discomfort Glare and Disability Glare.

Bright sources of light in the field of view of the eye produce glaring effects, of which at least two can be distinguished. First, there is the effect which the glaring light sources have on the ability to see; thus objects which are invisible or can only be seen with difficulty when the glaring sources are in the field of view are revealed when the sources are screened from the observer. Second, there is the effect which glaring light sources have on the comfort of the observer. Glaring sources which may have but a small effect on the ability to see may yet cause very considerable distraction and discomfort.

The disabling and the discomforting effects of glare do not appear to be directly interlinked. This is particularly noticeable on lighted streets. In many streets the ability to perceive objects is affected only very slightly by the presence of unscreened light sources, yet "glare" is complained of because the presence of the sources distracts the attention or gives rise to a feeling of discomfort. It is with this second effect, to which the term *Discomfort Glare* has been given, to distinguish it from the first effect, *Disability Glare*, that the present investigation is concerned.

The problem of disability glare has been investigated by several workers (1), of whom Luckiesh and

(1) Luckiesh and Holladay, Trans. I.E.S. (U.S.A.), vol. 20, p. 221.
Holladay, J., Opt. Soc. Amer., vol. 12, p. 271.
Holladay, Trans. I.E.S. (U.S.A.), vol. 22, p. 290.
Bordoni, L'Elettrotecnica, vol. 11 (Sept. 5, 1924).
Stiles, Proc. Roy. Soc., vol. 104 (B), p. 322; I.E., vol. 23, p. 279 and vol. 24, pp. 162 and 187.
Crawford, Proc. Phys. Soc., 1936, p. 35.
Dunbar, Trans. Illum. Eng. Soc. (Lond.), vol. 3, p. 187.

Holladay, Stiles, Crawford, Dunbar, and Bordoni have made contributions which have enabled quantitative allowance to be made for disability glare effects in problems of street lighting design.

The present work was inspired by the fact that some installations which were generally described as "glaring" could be shown, by the application of the Holladay-Stiles expression (2), to be affected only in small degree by disability glare. In many cases calculation indicated that the revealing power of the installation was hardly affected by the presence of unscreened sources of light. Such examples confirmed that discomfort effects are often of greater magnitude than disability effects in the problem of glare in lighted streets.

The degree of discomfort caused by glare cannot be measured, because discomfort is a sensation experienced by the individual, and no means of measuring the magnitude of a sensation have ever been devised. It is, however, conceivable to investigate discomfort glare quantitatively by measuring the magnitude of the contributing factors when some fixed and recognisable amount of discomfort has been produced. This is the guiding principle of the present investigation. After the initial difficulties of devising a satisfactory technique had been overcome, it was found possible to accumulate a large amount of data bearing on the problem.

2. Principles of the Measurements.

(i) Observers.

The sensations of discomfort or distraction are resident in the observer himself. The only way in which any notion of the magnitude of such sensations can be communicated to the outside world is by a conscious indication from the observer (3). The observer, therefore, must be a person capable either of interpreting in words the nature, or magnitude, of the sensation of discomfort which he experiences from a given set of conditions, or else of giving an indication when he experiences a sensation identical with that previously described to him, and must be fully capable of understanding the nature of the observations required of him, if accurate indications of the nature of his sensations are to be obtained. In the present work it was, therefore, not attempted to obtain data from a very large number of persons chosen at random. Observations have been confined to about thirty selected observers who were known to fulfil the required conditions.

(ii) Criterion of Discomfort Glare.

The principle of these measurements has been the recognition of four degrees of discomfort glare, these degrees of glare being obtained by suitable alteration of the conditions obtaining in the street lighting installation. These degrees of glare are as follows:—

A. *Just intolerable.* The change-over point between intolerable and uncomfortable glare. The glare is definitely very uncomfortable, and any increase in the glare would produce intolerable glare.

B. *Just uncomfortable.* The point where the glare is definitely distracting but only just uncomfortable. The term "uncomfortable" is associated in some observers with the desire to shade the eyes from the glare sources. The term "distracting" implies that the sources are sufficiently noticeable to attract the observer's attention.

C. *Satisfactory.* The point where the sources though still noticeable, are deemed sufficiently unobtrusive to cause no distraction.

D. *Just not perceptible.* The point where the glare is just no longer noticeable. The sources are still visible, but merge into the general field of view in such a way as no longer to attract the eyes of the observer.

These four degrees of glare were found by experience to be most easily recognised. They will subsequently be referred to, particularly when tabulating data, as Criteria A, B, C, and D.

3. Conditions which Give Rise to Discomfort Glare.

In an artificially lighted street the physical brightness of the light sources is almost invariably many hundred times greater than the general brightness level of the rest of the field of view. The adaptation of the eye must depend to some extent upon the general brightness of that region of the scene on which attention is mainly directed, which in the case of a car driver is that region of the carriageway and pathways round about 300 ft. from the observer, or, in the case of a pedestrian, a rather more extended region of the street. The surroundings

(2) $\beta = B + \Sigma k \frac{E}{\theta^n}$

where B = background brightness against which an object is seen, E = illumination produced on the eye by each glare source, θ = angular separation of each glare source from the line of sight, β = background brightness in absence of glare for which the brightness difference threshold is the same; k and n are constants. (n = 2 approx.)

(3) An exception to this is perhaps the technique employed by Luckiesh and Moss (Jour. Exper. Psych., vol. 16, p. 540, and Jour. Gen. Psych., vol. 13, p. 131), by which ease of reading was assessed by measurement of the rate of heart beats, or by estimation of the nervous muscular tension of the observer. This method is not directly applicable to the present investigation.

of the scene also must affect the adaptation level, but probably to a smaller extent. The presence of the bright but small sources can have only a relatively small influence on the general adaptation level, first, because they are remote, in varying degree, from the area of the scene in which the eye is interested, and, second, because they occupy a relatively small part of the field of view. Consequently, the eye is adapted to a level of brightness of the same order as that of the important region of the street scene, and is not adapted to the high brightness of the sources, which may therefore give rise to discomfort glare. The degree of this discomfort will be determined, amongst other factors, by the apparent brightness of the sources, and will increase with it. The higher the general brightness level of the scene, the less discomfort will be caused by a given glare source. Thus, in daylight, the glare from a motor-car headlight is negligible.

Discomfort glare will be influenced not only by the apparent brightness of the glare sources, but also, for example, by the position which these sources occupy in the scene, a source near the point of interest causing more discomfort or distraction than one farther away; or by the apparent size of the glare source, i.e., by the solid angle which each source subtends at the eye of the observer. (Fig. 1.)

In practice the effect on glare of the position of each source in the field of view is closely influenced by the light distribution of the lanterns installed in the street. For simplicity it has been arranged in much of the work about to be described that the intensities of all lanterns in the field of view are the same. In practice this is not so, since the lantern intensity varies in both azimuth and elevation; and, in fact, the " peak " intensity shown on a laboratory polar curve may seldom reach a driver's eye.

Fig. 1.

An idea of the correlation between the iso-candle distribution and the view of the glaring sources can be obtained by the device shown in Fig. 2, in which

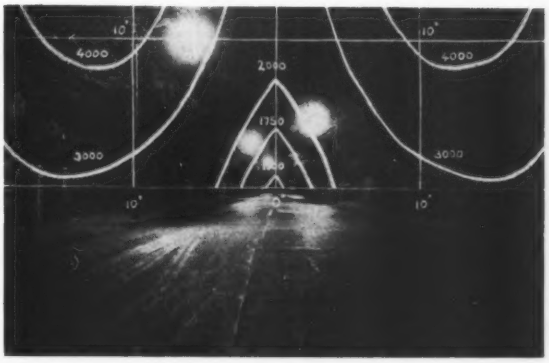

Fig. 2. Isocandle diagram plotted on photograph.

the relevant part of the iso-candle diagram is superimposed, upside down, on the photograph, using the appropriate scale of degrees. Since the " street side " of the lanterns on each side of the road is seen, the " street side " of the distribution is repeated for the off side of the road.

From this diagram the intensity of each lantern in the observers' direction can be read off by interpolating between the contours and the value corresponding to the position of the lantern. An estimation can also be made of the intensities which would be found for different positions of the observer and lanterns.

To these objective factors must be added subjective factors depending upon the observer himself; his prejudices concerning glare; the physiological characteristics of his vision, which together with his general state of health will determine his susceptibility to glare; and others.

4. Points to be Investigated.

(i) Do people differ widely from one another in the opinions which they form of the discomfort experienced in a given street lighting installation? If so, to what extent do they differ, and why? Do the majority concur in an opinion, or are opinions spread over a wide range?

(ii) Can observers recognise consistently a given

degree of glare, under various conditions and on different occasions?

(iii) Upon what factors does discomfort glare depend; for example, in what way is the glare influenced by:—

(a) the intrinsic brightness of the source
(b) the solid angle subtended at the eye by the source and hence
(c) the intensity of the source
(d) the general level of background brightness
(e) the position of the glare source in the field of view.

(iv) Are the individual glare effects of single sources additive?

5. Experimental Technique.

The subjective nature of the work renders it essential to make the observations under as nearly as possible practical conditions. It was realised that to obtain sufficient observations on actual streets would involve an impracticable amount of night work. It was also obviously impracticable to study independently all the objective factors listed in Section 4 above by experiments on actual streets.

The work was therefore conducted in a model street. In order to check the validity of this procedure, opportunities were taken from the start of the work to compare the results obtained in the model street with those obtained under comparable conditions on existing installations.

(i) Apparatus.

The model in which the experiments were made consisted of a box, blackened inside, having at one end an observation hole and at the other a standard representation photograph of a street lighting installation [4] at a distance of 55 cm. from the observer's eyes, this distance giving the correct perspective for the photograph chosen. (See Fig. 3.) The photograph was illuminated by a tungsten filament lamp which was hidden from the observer. The brightness of the picture could be varied by means of a resistance in series with this lamp. In the photograph were pierced holes where the images of the sources of the installation occurred. These source apertures were illuminated from behind by a large condenser lens flashed to the required brightness by a tungsten filament projector lamp. The intrinsic brightness of the flashing of the condenser, and thus of the glare source apertures, could be varied by another resistance in series with the projector lamp.

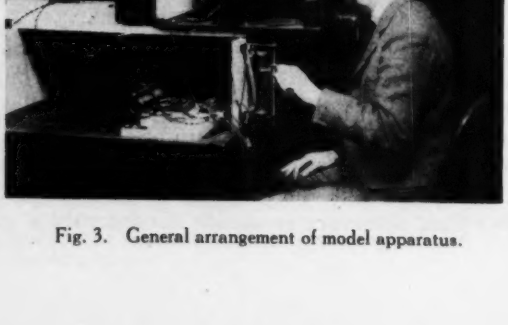

Fig. 3. General arrangement of model apparatus.

The apparatus thus constituted a model street with glare source brightness and general background brightness variable independently of one another. The design of the apparatus provided that the field of view of the observer corresponded approximately with that seen from the driving seat of a car. Auxiliary lamps, hidden from the observer, in parallel with the lamp illuminating the picture, provided a low level of illumination on the interior of the box, thus corresponding to the low level of illumination inside a motor-car produced by the street lamps.

The observation hole was large enough to enable the observer to use both eyes. The condenser flash, and hence the glare source apertures, appeared equally bright to both eyes. This was made possible by means of a spherical mirror behind the projector lamp, which produced a real image of the filament slightly to one side of the actual filament, in such a manner that two images of the filament were produced in the plane of the observer's eyes, one image on each eye. The two images were diffused and the brightness of the flashing was made uniform by interposing between the lamp and the condenser lens an etched glass screen. The observer's head was located by means of a chin rest in the correct position to receive the two images of the lamp on his eyes. This rest permitted a small amount of movement, such that the observer could find a comfortable attitude, whilst retaining the correct viewing position.

For calibration purposes the brightness of the standard representation photograph was measured at a

(4) Hopkinson, The Photographic Representation of Street Lighting Installations, Trans. Illum. Eng. Soc. (Lond.), vol. 1, p. 19. A standard representation photograph is a photograph produced to conform to a specified contrast and density scale, such that an accurate impression of the original scene is thereby given.

point (A on Fig. 1) which corresponded to a point on the carriageway 300 ft. from the observer. The average brightness of the whole of the photograph which constituted the field of view of the observer for the

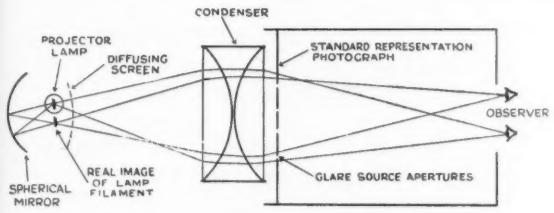

Fig. 4. Optical arrangement of apparatus.

experiments was measured and found to be 0.36 of the brightness of the calibration point.

The standard representation photograph which was used for a number of the observations was provided with an arrangement by which the area of each of the glare sources could be separately adjusted. Behind each of the holes cut in the photograph in the source positions was fixed a small device consisting of two V-leaves, one of which moved across the other, its movement being controlled by a micrometer mechanism. The area of the aperture, therefore, depended on the relative positions of the V-leaves.

For other series of observations exact copies of this standard representation photograph were employed in the model, each photograph being fitted with the arrangement of source apertures appropriate to the particular investigation for which it was required.

(ii) Observing Technique.

Prior to the development of the main investigation a series of preliminary observations was made in order to establish a suitable technique for obtaining the data required. The procedure finally adopted was as follows.

The observer sat at the model, adjusted his eye position, and waited five minutes for his eyes to adapt to the scene set up before him. The brightness of the glare sources was adjusted to a given value by the person recording the readings. The observer was given control of the brightness of the standard representation photograph and was asked to adjust this brightness until the degree of glare corresponded to a criterion previously defined to him. He was asked not to study any particular feature of the road surface, but to look ahead as he would if he were driving along the road. He was not to judge the glare by what he could or could not see, but entirely by his feeling of comfort; it was usually possible for the recorder to judge by the replies given by the observer to suitable questions whether this condition was being fulfilled.

The observer was asked to make four separate settings of surround brightness, which corresponded to each of the four distinct degrees of glare, just intolerable, just uncomfortable, satisfactory, and just not perceptible, which have been defined on page 2. Great care was taken to ensure that all observers interpreted these criteria in the same way. The recorder asked questions, the replies to which indicated whether the correct interpretation was being made.

It was found that this procedure led to the greatest consistency in the results, probably because the separate degrees of discomfort could be accurately defined in relationship to one another. The preliminary observations showed that it was of considerably greater value to ask for single settings for each of four clearly defined degrees of glare than to ask for a number of settings of one loosely defined criterion with a view to obtaining the mean of these settings.

The preliminary observations also demonstrated without any doubt that observers, for some reason, experienced much more difficulty in making their observations when they were asked to control the brightness of the sources than when they controlled the brightness of the picture. This was evident both from the fact that readings did not plot well and by the complaints which observers made of difficulty or of fatigue. At a later stage of the work readings were obtained from three observers which showed, however, that there was no significant difference between the order of the results obtained by the two methods. Since the method in which the observer controlled picture brightness, and the recorder the source brightness, was less difficult for most observers, it was therefore adopted.

All experiments were so conducted that sudden large changes in the brightness of the photograph were avoided. During the course of an experiment the brightness of the photograph was raised, but was rarely lowered by any large amount. These precautions were taken in order to avoid, as far as possible, errors due to the observer's eyes failing to adapt sufficiently quickly to the change in surround brightness. (The eye takes considerably longer to adapt to lower brightnesses than to higher brightnesses.)

Observers who had considerable experience of making estimations of glare in street lighting installations were able to proceed with the measurements

immediately after the period of dark adaptation, but observers who had not had such experience spent ten minutes in making certain detailed preliminary observations. This was found to be important. These observations educated the observer to an understanding of the nature of the readings required, but did not in any way prejudice his opinions.

6. Summary of Results.

The experimental work involved in the investigation was necessarily lengthy; it may therefore be of advantage to give a summary of the main conclusions arising from the work before reporting in greater detail on the experimental work.

(i) Additive Nature of Individual Glare Effects.

If the surround (road) brightness with which each of a number of single sources gives a certain degree of glare is measured in each case, the arithmetical sum of these brightnesses agrees closely with the measured value of surround (road) brightness chosen to give the same degree of glare when all the sources are presented together.

This is an interesting result of considerable practical value. It implies that the conditions necessary to establish a given degree of glare in a complete installation can be estimated provided the conditions necessary for the same degree of glare are known for the individual sources of the installation.

(ii) Effect of General Background Brightness on Glare.

The general brightness level of an installation is an important factor in determining the magnitude of the glare from the installation. If, in an installation, the conditions are such that the glare is considered to be "just uncomfortable," a reduction in the general average brightness level to one-fourth of its former value, the glare sources not being altered in any way, would increase the glare such that it would be considered "just intolerable." On the other hand, if the general brightness level had been increased four times the glare would be decreased such that it would now be considered "satisfactory." A further increase of four times in the general average brightness level would decrease the glare to "just not perceptible."

Other things being constant, a change of $\pm$ 30 per cent. in the value of the road brightness produces a just appreciable alteration in the glare conditions.

(iii) Empirical Expression Correlating Objective Factors Influencing Glare.

The dependence of the glare effect upon the other variables of the installation is given by the following expression:—

For a given degree of discomfort glare,

$$B_b = k.\frac{B_s^{1.3}\omega}{\theta^{0.75}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

or $$B_b = c.\frac{E\,B_s^{0.3}}{\theta^{0.75}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

or $$B_b = c.\frac{I^{1.3}}{A^{0.3}\,\theta^{0.75}\,d^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

where B_b = background brightness (equivalent foot-candles) expressed by the brightness of a point 300 ft. away on the carriageway.

B_s = intrinsic brightness of source (candles/sq. inch).

ω = solid angle subtended by the source at the eye (steradians).

θ = angle between direction of source and line of sight (5) (degrees).

E = illumination on the eye from glare source (foot-candles).

I = intensity of source in direction of the eye (candles).

A = flashed area of source (sq. inches).

d = distance of source from observer (ft.).

Using these expressions, the following constants apply:—

Degree of glare	k.	c.
A. Just intolerable ...	115	0.8
B. Just uncomfortable ...	450	3.1
C. Satisfactory	1700	12
D. Just not perceptible...	7000	50

These three forms of the expression give the average background brightness with which a given degree of glare would be produced by one source in the field of view. If several sources are present, the background brightness with which the same degree of glare would be produced is given by the sum of the separate values of background brightness corresponding to each source. Thus:—

$$B_b = k\Sigma\frac{B_s^{1.3}\omega}{\theta^{0.75}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where k has the same value for the same degree of glare.

(5) See Appendix III.

The curves (Fig. 5-8) shown below and Tables I.-VI. (page 8) illustrate the inter-relationship of these variables when applied to street lighting installations of common type. The curves and tabulated figures apply to the case of equal intensities from each source in the direction of the eye. The tables are computed for an installation extending 800 ft. from the observer; thus if the spacing is 150 ft., five sources are present.

Both tables and curves summarise the results of experiments, and are, of course, not necessarily recommendations for limits for discomfort glare in practice. They should, therefore, be interpreted in this light.

These results can, on the other hand, be correlated with practice if it is realised that the values of B_b (background brightness) represent the brightness of the calibration point of the scene employed in all the experiments, this point appearing to be situated 300 ft. from the observer, on the carriageway (Fig. 1), and therefore representing the important part of the background at which attention is most likely to be directed. Useful comparison can therefore be made

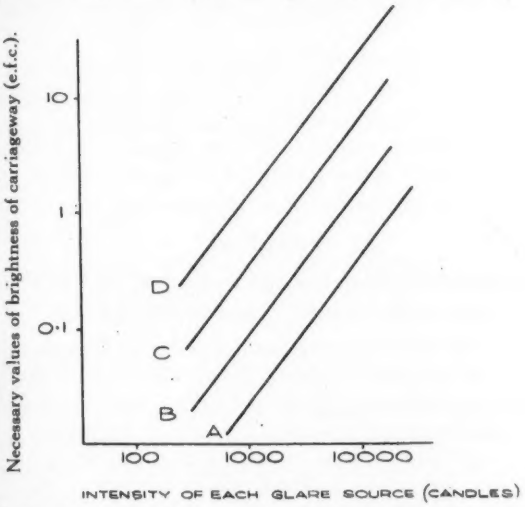

Fig. 5. Correlation between source intensity and carriageway brightness for four given degrees of glare. Source flashed area constant at 100 sq. inches, the change in source intensity being obtained by change in source intrinsic brightness. (Weighted mean curves for installation of Fig. 1, Mtg. Ht. 25 ft. Spacing 150 ft. diagonal.)

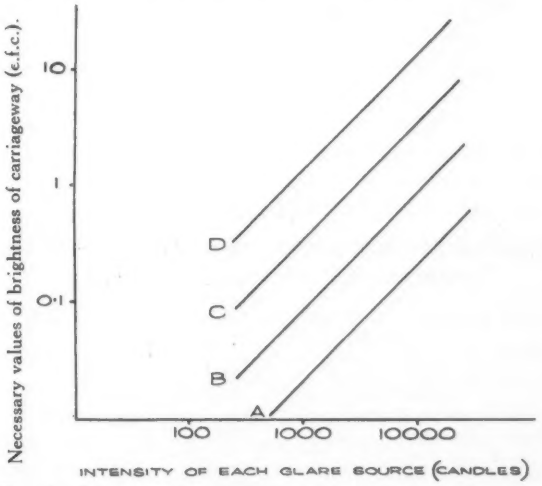

Fig. 6. Correlation between source intensity and carriageway brightness for four given degrees of glare. Source intrinsic brightness constant at 10 candles/sq. inch and the source area varied. (Weighted mean curves for installation of Fig. 1, Mtg. Ht. 25 ft. Spacing 150 ft. diagonal.)

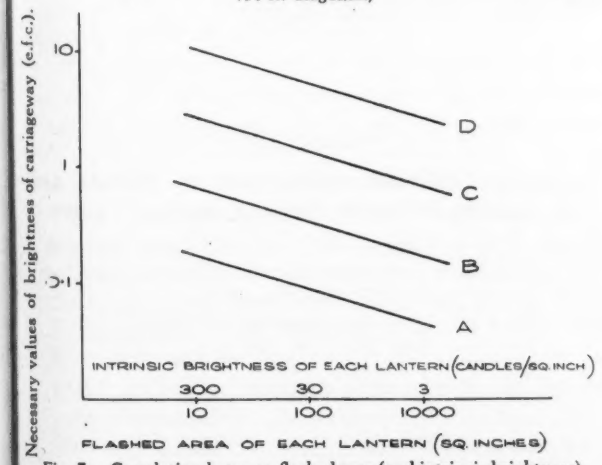

Fig. 7. Correlation between flashed area (and intrinsic brightness) of sources and carriageway brightness for four degrees of glare. Source intensity constant at 3,000 candles. (Weighted mean curves for installation of Fig. 1, Mtg. Ht. 25 ft. Spacing 150 ft. staggered.)

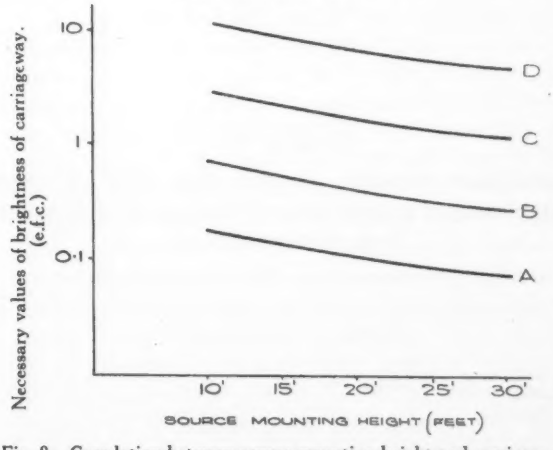

Fig. 8. Correlation between source mounting height and carriageway brightness for four degrees of glare. Source intensity constant at 3,000 candles, spacing 150 ft. diagonal, source area 100 sq. inches, source intrinsic brightness 30 candles/sq. inch. (Weighted mean curves.)

TABLE I.

Correlation between source intensity and carriageway brightness for four degrees of glare.

Source flashed area constant at 100 sq. inches, the change in source intensity being obtained by change in source intrinsic brightness.

Mtg. Ht. 25 ft. Spacing 150 ft. staggered. Source area 100 sq. in.

Source intensity (equal for all sources) candles.	Carriageway Brightness (e.f.c.)			
	A. Just Intolerable	B. Just Uncomfortable	C. Satisfactory	D. Just not Perceptible
300	0.005	0.02	0.07	0.3
1000	0.02	0.1	0.3	1.5
3000	0.1	0.4	1.5	5.0
10000	0.4	1.5	6.0	25

TABLE II.

Correlation between source intensity and carriageway brightness for four degrees of glare.

Source intrinsic brightness constant at 10 candles/sq. inch and the source area varied.

Mtg. Ht. 25 ft. Spacing 150 ft. staggered. Source brightness 10 candles/sq. inch.

Source intensity (equal for all sources) candles.	Carriageway Brightness (e.f.c.)			
	A. Just Intolerable	B. Just Uncomfortable	C. Satisfactory	D. Just not Perceptible
300	0.007	0.03	0.1	0.4
1000	0.02	0.1	0.3	1.5
3000	0.07	0.3	1.0	4
10000	0.2	0.8	3	15

TABLE III.

Correlation between flashed area (and intrinsic brightness) of sources and carriageway brightness for four degrees of glare.

Source intensity constant at 3,000 candles.

Intensity of each source 3000 candles. Spacing 150 ft. staggered. Mtg. Ht. 25 ft.

Lantern flashed area (sq. in.)	Intrinsic brightness (candles sq. in.)	Carriageway Brightness (e.f.c.)			
		A. Just Intolerable	B. Just Uncomfortable	C. Satisfactory	D. Just not Perceptible
10	300	0.2	0.7	3.0	10
100	30	0.1	0.4	1.5	5.0
1000	3	0.05	0.2	0.7	2.5

TABLE IV.

Correlation between source mounting height and carriageway brightness for four degrees of glare.

This table does not include the effect of change of height upon change of brightness distribution on the road (6).

Intensity of each source 3000 candles. Spacing 150 ft. staggered. Source area 100 sq. in. (intrinsic brightness 30 candles/sq. in.).

Mounting Ht. (ft.)	Carriageway Brightness (e.f.c.)			
	A. Just Intolerable	B. Just Uncomfortable	C. Satisfactory	D. Just not Perceptible
10	0.2	1.0	3.0	12
20	0.1	0.4	2	7
30	0.08	0.3	1.5	5.0

TABLE V.

Correlation between spacing of sources and carriageway brightness for four degrees of glare.

This table does not include the effect of a change of spacing on the brightness distribution on the road.

Intensity of each source 3000 candles. Mtg. Ht. 25 ft. Source area 100 sq. in. (intrinsic brightness 30 candles/sq. in.) Staggered arrangement.

Spacing (feet)	Carriageway Brightness (e.f.c.)			
	A. Just Intolerable	B. Just Uncomfortable	C. Satisfactory	D. Just not Perceptible
100	0.2	0.8	3.0	12.0
150	0.1	0.4	1.5	6.0
200	0.06	0.25	1.0	4.0

TABLE VI.

Correlation between arrangement of sources and carriageway brightness for four degrees of glare.

Intensity of each source 3000 candles. Source area 100 sq. in. (intrinsic brightness 30 candles/sq. in.) Spacing 150 ft. Mtg. Ht. 25 ft.

Arrangement	Carriageway Brightness (e.f.c.)			
	A. Just Intolerable	B. Just Uncomfortable	C. Satisfactory	D. Just not perceptible
Staggered ...	0.1	0.4	1.5	5.0
Single side left	0.1	0.4	1.5	5.0
Single side right	0.1	0.4	1.5	5.0
Central ...	0.12	0.45	1.6	5.5

(6) G. H. Wilson, Assoc. Public Lighting Eng., 1937.

between the laboratory experiments and practical conditions, if the tabulated values of B_b are compared with the brightness of a similar important part of the scene. This significant area of the scene must be selected by judgment in every case: it cannot be defined universally on account of differences between scenes.

The tables give the values of carriageway brightness (B_b) with which the given conditions (of intensity, etc.) would produce given degrees of glare. (The accuracy of the readings upon which these results are based is of the order of ± 50 per cent.)

In all the experiments of which the preceding tables summarise the results the brightness of the carriageway, etc., was independently controlled and did not vary with change of the lighting installation; the brightness necessary to permit some given degree of glare was determined by altering the independent control.

In practice, however, an alteration of the installation does affect the brightness level and distribution, to a degree which depends on the light distribution, the road surface and other factors. In any given case, therefore, in order to find the final effect of an alteration in (say) height, the effect of change of mounting height on the brightness distribution and level must be assessed; and it must be decided whether the brightness necessary to permit some given degree of glare will in fact occur. This cannot be done precisely in the general case because the conditions are not the same in all installations.

(iv) Relative Glare Effect of Coloured Light Sources.

The colour of the light source, whether yellowish, bluish, or white, does not appear to influence the degree of discomfort glare to any appreciable extent

7. Accuracy of Results.

The results naturally showed a very wide spread. For any one observer, the spread between readings of road brightness for a given degree of glare was of the order of $\pm$ 50 per cent. This spread was, rather unexpectedly, fairly constant over the whole range of brightness explored.

The spread of readings was greater for less able or less experienced observers.

It was found that, once an observer had established his criterion, the spread between any two of his readings was almost the same whatever the intervening period, whether an hour or a week, provided that no radical change in the observer's state of health had taken place. Occasionally, readings widely different from the mean were given, but these could usually be traced to an altered criterion, of which the observer was often aware and which he could correct.

A statistical analysis was made of the readings obtained by a number of observers under identical conditions. It was found that the disposal of readings about the mean followed approximately the Gaussian or normal distribution.

The variability of any one observer from time to time expressed in terms of the standard deviation of his readings made under identical conditions was $\pm$ 55 per cent. The results obtained by a number of typical observers were pooled in order to arrive at this figure.

The variability of the mean readings of all the observers about the common mean was $\pm$ 26 per cent. This is rather greater than would be expected if the differences between the means had been due to chance alone. These differences between observers are therefore very probably real and may be due to differences in sensitiveness to glare or to small differences in the criterion adopted.

These figures apply to the variability of readings on a complete installation. The degree of accuracy of those readings for which one source only was exposed could not be found in the same way, because there were not sufficient repeat readings under identical conditions to enable the variability to be assessed on the basis of repeat readings. The standard deviation of such readings from the mean *curves* was, however, measured, and found to be $\pm$ 55 per cent., indicating that the variability of the observers who were able to make these readings was of the same order as that of all the observers concerned with the readings on the complete installation. For any one observer, though, the variability was rather greater for readings with one source only exposed than with a complete installation exposed.

When the results of the investigation are being studied, therefore, it will be remembered that:—

(a) There will be one chance in five of an observer making a reading more than $\pm$ 50 per cent. from his mean value. Therefore, any differences less than $\pm$ 50 per cent from the mean must be ignored as within the limits of the experimental technique.

(b) The four degrees of glare chosen for the investigation are well separated. There is only one chance in 600 of an observer confusing, by his readings, one degree of glare with another, provided his

state of health and his criterion of glare do not suffer a change.

8. Application of Results to Problems of Street Lighting Design.

The results of the investigation which have been given above have been put into a form which is convenient for their direct application to problems of street lighting design.

A brief note on the application of the results to such problems follows.

(i) Estimation of Probable Degree of Discomfort Glare in an Installation.

The degree of glare likely to obtain in an installation, the equipment, arrangement, etc., of which have already been decided upon from a consideration of factors other than those of discomfort glare, can be calculated directly from the empirical expression on page 6, i.e.,

$$B_b = c\Sigma\frac{I^{1.3}}{A^{0.3}\,\theta^{0.75}\,d^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots(5)$$

The value of B_b is first found in terms of the constant c. In the case of an installation not yet erected a further calculation is necessary in order to obtain the probable value of road brightness likely to obtain in the installation on the particular road surface. (7)

The value of road brightness is then equated to ΣB^b and the constant c evaluated. Hence, by application of the value of c to the glare scale of Fig. 9, the degree of glare to be expected in the proposed installation can be estimated.

If the road surface reflection properties are known it is possible, though laborious, to calculate the brightness distribution on the surface. In practice the brightness can perhaps best be estimated from experience.

(ii) Means of Reducing Discomfort Glare.

There are several methods by which glare can be reduced, applying the principles deduced from the investigation. Discomfort glare is, however, only one of the many variables which combine to determine the excellence of an installation. Any reduction in discomfort glare which is accompanied by a disproportionate reduction in the general excellence of the installation must necessarily defeat its purpose.

(a) *Increase of the flashed area of the sources.* An increase of the flashed area of the sources, the intensities being retained constant, will bring about a reduction of discomfort glare, although it will not reduce the disability glare. This method is of value, because it does not affect the revealing power or the brightness of the installation, so long as the light distribution from the lanterns is unaffected. If any appreciable reduction in discomfort is to be obtained, however, the flashed area of the lantern must be at least doubled.

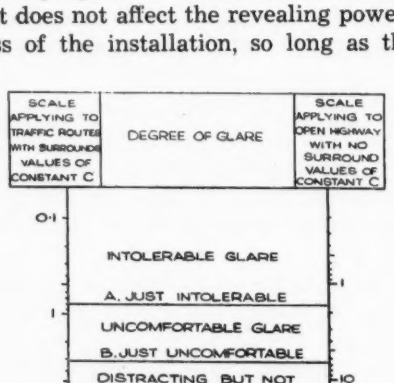

Fig. 9. Scale of discomfort glare. Values of constant C in expression $B_b = C\Sigma\frac{I^{1.3}}{A^{0.3}\,\theta^{0.75}.d^2}$ correlated with degrees of comfort.

(b) *Increase of mounting height.* The discomfort glare from an installation of sources mounted at 15 ft. would be reduced noticeably if the sources were mounted at 25 ft., provided the brightness of the road surface did not suffer in consequence. (6) A noticeable advantage would be gained on most traffic routes, where the road surface has usually a fair degree of polish.

(c) *Reduction of spacing of lanterns.* A more closely-spaced installation of sources of lower intrinsic brightness will probably be less glaring than a longer spaced installation of sources of high intrinsic brightness for a given power expenditure per unit length of road.

(d) *General reduction of source intensities by reduction of source intrinsic brightness.* A general reduction of the intensities of all the sources of an installation by reduction of the intrinsic brightnesses of the sources (e.g., by substitution of lower-powered

(7) Such calculation can be performed from a knowledge of the reflection characteristics of the road surface. See "Road Surface Reflection Characteristics and Their Influence on Street Lighting Practice," J. M. Waldram, A.P.L.E., 1934, and I.E. vol. 27, p. 305. A. Bloch, Trans. Illum. Eng. Soc. (Lond.), vol. 4, p. 113.

lamps, retaining the same lantern flashed area) will reduce somewhat the degree of discomfort glare obtaining, but the method should not be employed unless it is certain that the reduction in discomfort glare more than outweighs the loss of revealing power. This is unlikely to be the case in any installation erected at the present time.

(e) *Change of light distribution from lanterns.* The less the intensity produced by a lantern in the direction of the eye of the observer, the less discomfort it will produce for a given background road brightness. Therefore, if the intensities of the glare sources are reduced, at the same time retaining constant the general background brightness, the discomfort glare will be reduced. This ideal is attained by the complete cut-off type of installation, provided that the spacing is sufficiently close and the available light flux sufficient to give a high road brightness. Economic factors, however, usually prevent so easy a solution of the glare problem. As has often been pointed out, it is in just those directions which cause glare to the observer that the light sources of an installation have to emit fairly high intensities if uniform brightness and adequate revealing power are to be attained with reasonable spacing and cost. Reduction of intensity in these directions with the aim of reducing discomfort glare will therefore result in a less pleasing installation with a lower revealing power, or else may require a shorter spacing and possibly a more expensive arrangement of lanterns. Discomfort glare is to a large extent complementary to the economical provision of high road brightness, high revealing power, and otherwise good appearance.

If the light distribution is progressively varied from an equal candle-power in all directions above 70° through the more usual non-cut-off and semi-cut-off forms to a complete cut-off, the spacing and wattage necessary to maintain a satisfactory brightness level and distribution will involve an increasing cost, but the discomfort glare will progressively decrease.

A series of calculations has shown that there is, on the whole, little to choose between good light distributions of each of these types, inasmuch as none of them enables installations to be made with much less

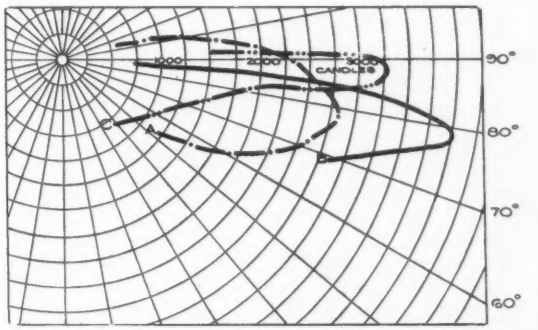

Fig. 10. Polar curves through the peak intensities of three distributions.

discomfort glare for the same cost, or vice versa. There are, of course, many poor distributions which produce little effect except discomfort glare.

This conclusion can be illustrated by an example. Fig. 10 illustrates three distributions, which have been designed to provide economically a high road brightness and revealing power. Distribution A is that from a lantern employing a vertical burning

TABLE XIII. Relative Discomfort Glare Effects of Three Typical Distributions.

Installation :—Mounting Ht. 25 ft. Spacing 150 ft. Flashed area of each source 100 sq. in.

Values of intensities adjusted to give an average road brightness of approximately 0·5 e.f.c. in all three cases, on a semi-polished asphalt service.

Source No.	Source distance (ft.)	I			$I^{1.3}$			$\theta^{.75}$	$B_b = \frac{c.I^{1.3}}{A^{0.3}\,\theta^{0.75}\,d^2}$		
		A	B	C	A	B	C		A	B	C
1	150	2750	3200	2000	29500	37000	20000	5.1	.064c	.08c	.043c
2	300	2500	1750	3200	26400	17000	37000	3.5	.021c	.013c	.029c
3	450	2450	1000	3200	26000	8000	37000	2.3	.014c	.004c	.020c
4	600	2400	950	3200	25500	7500	37000	2.1	.009c	.003c	.012c
5	750	2350	900	3200	25000	7000	37000	1.6	.007c	.002c	.010c
								ΣB_b	0.115c	0.102c	0.114c
								$c = \frac{0.5}{\Sigma B_b}$	4.35	4.9	4.4

h.p.m.v. light source. Its chief feature is that the intensity between 75° and 90° to the downward vertical varies very little. Distributions B and C are distributions which have been proposed, with the purpose of reducing glare. Distribution B has actually been adopted, the chief feature of this distribution being a controlled "run-back" above 80° to the vertical. Distribution C has been proposed because it arranges for the main beam from the nearer lanterns to pass above the eyes of the observer, whilst the more distant lanterns still produce a high road brightness and revealing power.

The degree of discomfort glare can then be calculated as in Table XIII.

Each distribution would produce approximately the same degree of discomfort glare (about "just not uncomfortable," see Fig. 9), in spite of the obvious differences between the distributions. It should be noted that this conclusion does not apply to disability glare.

This conclusion applies in the main to changes in the light distribution in the vertical plane. So far no intensive study has been made of the effects of changes of distribution in a horizontal plane on the general appearance of the roadway. It is therefore not possible, at this stage, to suggest recommendations for such changes of distribution. As an example, however, an improvement in discomfort glare, with no consequent deterioration of the general excellence of the installation, could undoubtedly be produced in a high-powered installation on a road flanked by light-coloured buildings, if the illumination on these buildings were increased and the intensities in the direction of the eye reduced. The increase in general background brightness thus produced, together with the reduced intensities, would reduce the discomfort glare, whilst the consequent reduction of the road surface brightness would in this case be much less serious than in the case of an open highway, where the road surface is the only background against which objects can be perceived.

9. Experimental Work.

In the section that follows the experimental work of the investigation is described in greater detail under a number of separate headings into which the work can conveniently be divided.

(i) Readings to Obtain a Measure of the Consistency and Repeatability of Observations.

A standard representation photograph, an exact copy of that used in the preliminary investigation, was provided with fixed source apertures corresponding to an installation of lanterns of flashed area 100 sq. in., spaced at 150 ft. in staggered arrangement. This photograph will be referred to as the "standard" photograph.

The observer was asked to make settings of the background brightness to give each of the four degrees of glare, this being done at each of five intensity levels. Thus twenty readings were made at one session. This procedure was repeated by the observer on subsequent occasions, the interval between one set of readings and the next varying from a few hours to several weeks, and the complete series of readings being spread over a period of several months.

The readings thus made from time to time by any one observer were plotted on one graph in order to study the spread of the readings from time to time. After a sufficient number of readings had been obtained, mean curves could be plotted from the readings.

Typical results are given for one observer in Fig. 11. It will be noted that the readings at the

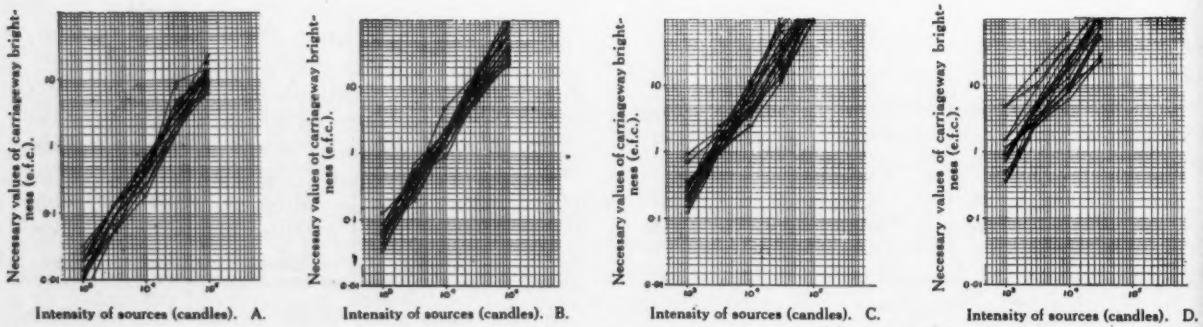
Necessary values of carriageway brightness (e.f.c.).
Intensity of sources (candles). A.
Intensity of sources (candles). B.
Intensity of sources (candles). C.
Intensity of sources (candles). D.

Fig. 11. Repeated readings of necessary values of carriageway brightness for four degrees of glare with installation of various source intensities.

extremes of the spread for this observer are about one and a half times the mean, whereas the difference between one degree of glare and the next is of the order of $\times 4$ in the case of this observer. Thus the extreme readings of one degree of glare do not overlap with those of the next degree, except for a few random readings.

Six observers made similar series of readings, the spread of readings in each case being of the same order. These measurements showed that observers are able to form a criterion of discomfort glare, and to retain it over a period of several months at least.

Mean curves were obtained from each set of readings made by any one observer. It was interesting to note that the spread of these mean readings (shown in Fig. 12) for five of the six observers is

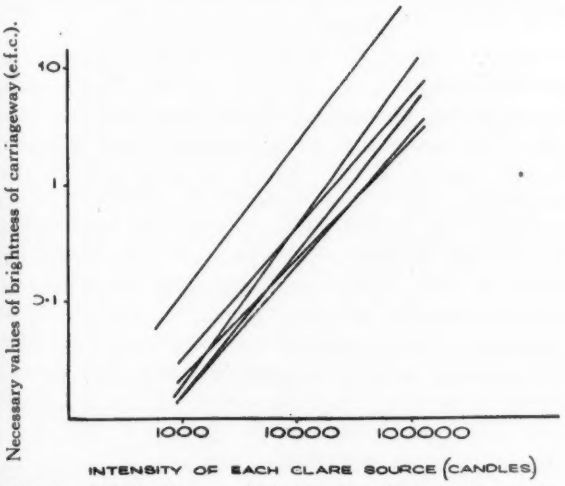

Fig. 12. Relation between background brightness and intensity of glare sources for "just tolerable" degree of glare for installation of Fig. 1. Mean curves for six observers.

rather less than the spread between the individual readings of one observer from time to time. The sixth observer, whose curve lies above the family of five, appeared consistently to set a different criterion of glare from the others. Further experiments where thirty observers took part indicated that this observer again set a different criterion from his colleagues, and it therefore seems reasonable to discount his results. On an actual installation he did not show any anomaly, his opinions being close to the average.

The results of a statistical analysis of these readings have been given in Section 7.

These mean readings obtained from the measurements made on the "standard" photograph served another purpose. In the subsequent investigations, it was the practice for observers to make a preliminary short series of readings under the "standard" conditions to ascertain whether, for some reason, they were making abnormal settings. If the short series differed slightly from the mean curve for the observer, the difference was ignored if it were small, or if it were larger, the subsequent set of readings was corrected by a factor corresponding to the relation between the observer's mean curve and the readings of his preliminary short series. Had a large difference been found the series would have been abandoned.

(ii) Dependence of Glare Effect in a given installation upon Source Intensity, Source Intrinsic Brightness, and General Background Brightness.

(a) Readings were made by fourteen observers, all of whom were street lighting engineers. For these measurements, the standard representation photograph described on page 4, was employed, this photograph representing a complete installation.

The source apertures were first adjusted to simulate an installation, the area of each source of which was 10 sq. in.; the source brightness being uniform, the model represented lanterns all of the same candlepower. For each given setting of source brightness (and therefore source intensity) made by the recorder, the observer was asked to make four adjustments to the background (road) brightness such that, in turn, the four degrees of glare, commencing with "just intolerable," were given by the installation. This was repeated for five settings of source intensity, covering the range 100 candles to 10,000 candles.

The source apertures of the photograph were next altered to represent an installation of sources, the area of each of which was 100 sq. in. A further complete series of measurements of background (road) brightness was then made by the observer covering the range 300 to 100,000 candles. This was repeated with the source apertures set to represent an installation of sources, the area of each of which was 1,000 sq. in., this series of measurements covering the range 300 candles to 100,000 candles. These measurements covered a range of intensities much greater than that prevalent under existing conditions of street lighting. It was thought that the true relationship over the street lighting range between the variables concerned would be found if this procedure were adopted.

A series of readings obtained by one observer is

shown in Fig. 13. The readings obtained by the other observers were all of the same order as those shown, and the readings of this observer may be taken as typical of this group of observers.

(b) Readings were made by nine observers, an this way, which is typical of this group of observers.

These readings have been treated separately from those of (ii) (a) (page 13) because the nine observers who made these readings had never previously made any measurements on street lighting installations,

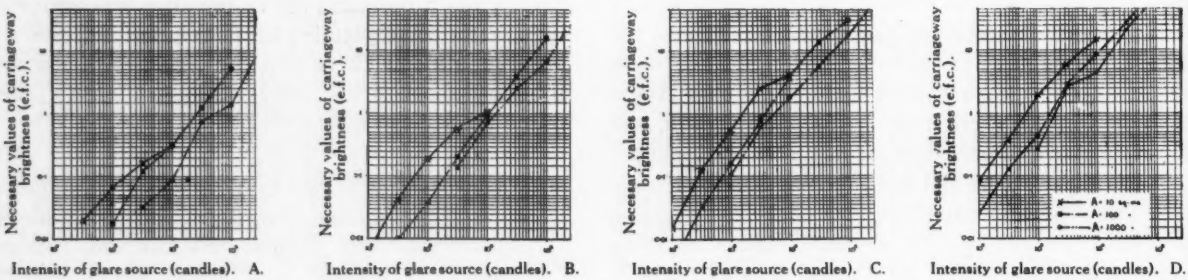
Necessary values of carriageway brightness (e.f.c.).
Intensity of glare source (candles). A.
Intensity of glare source (candles). B.
Intensity of glare source (candles). C.
Intensity of glare source (candles). D.

Fig. 13(*a*). Necessary values of carriageway brightness such that each of four degrees of glare are given by installations of different source intensities and source areas.

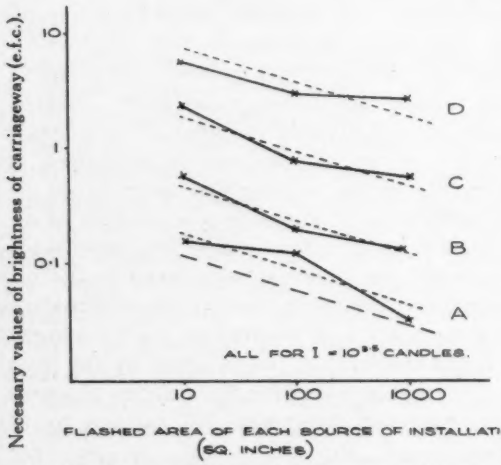

Fig. 13(*b*). Necessary values of carriageway brightness such that each of four degrees of glare are given by installations of different sizes of lantern. Readings of one observer.

exact copy of the standard representation photograph previously described being employed. This photograph was provided with source apertures corresponding to five installations with five values of source area (10, 31.6, 100, 316, and 1,000 sq. in.) and each of the installations could be separately presented to the observer. Observers made two sets of readings with this apparatus, the recorder setting the source intensity by (a) varying the source intrinsic brightness, the source area being retained constant at 100 sq. in. and (b) by altering the areas of the source apertures, the source intrinsic brightness being retained constant at 100 candles/sq. in.

Fig. 14 shows a series of readings obtained in

although they all had scientific training and experience.

(c) Series of readings were made by ten other observers along the same lines as those of section ii (b) above. These observers were not lighting engineers, but were chosen at random. These readings did not, in general, plot well, but showed the same general tendency as those previously obtained. Fig. 15 is a result typical of those obtained from observers of this group. Although these readings could not usefully be employed in obtaining a statistical mean of all observations, they were of value in showing that observers chosen at random

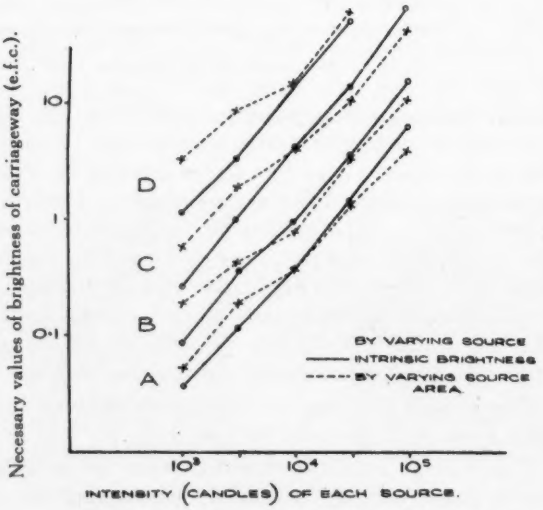

Fig. 14. Readings of one observer. (Section ii (*b*).)

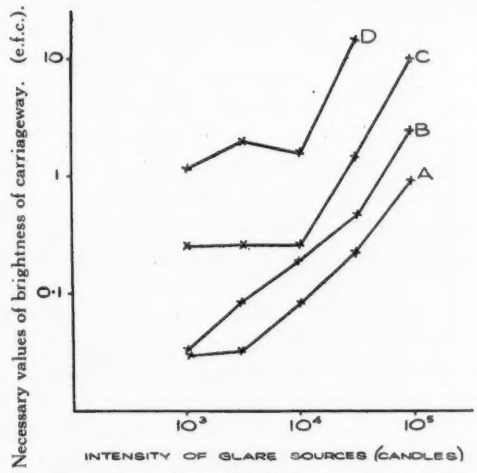

Fig. 15. Readings obtained under the "standard" conditions by an inexperienced observer. Readings do not plot very well, but demonstrate that they show the same tendency as those of experienced observers.

gave results of the same order as those observers chosen for their aptitude for making the necessary readings.

ANALYSIS OF RESULTS OF SECTION ii (a)—(c).

The readings of the twenty-three observers of Sections ii (a) and ii (b) were analysed statistically.

In every case it was found that, over the range of the experiments, approximate linear relationships held between log B_b (background brightness), log I (source intensity), and log A (source area) for constant glare conditions.

For constant source area, it was found that

$$\log B_b = g \log I + h \quad \ldots\ldots\ldots\ldots (6)$$

for the installation under observation.

The mean value of g was 1.3, the extreme values 1.15 and 1.5, and the standard deviation 0.094. This standard deviation is greater than would have been expected had the disposal of the individual readings about the best straight line been due to chance alone, and it would be justifiable to conclude that the variation in the value of g is probably due to differences in the vision of observers or in their criterion of glare.

For constant source intensity (i.e., reciprocal variation of source brightness and source area),

$$\log B_b = d \log A + e \quad \ldots\ldots\ldots\ldots (7)$$

The mean value of d was − 0.3, and the standard deviation 0.09. It was found that g of equation (6) and d of equation (7) were interdependent:—

$g + d = 1.0$ approx. for any given observer.

For constant source brightness, it was found that

$$\log B_b = a \log I + b \quad \ldots\ldots\ldots\ldots (8)$$

The mean value of a was 1.0, and the standard deviation 0.092. It was found that a depended upon g and d, the relationship $g + d = a$ operating for any given observer.

These three expressions were obtained from the independent experiments described in Sections ii (a) and (b) above. The inter-relationship of expressions (6), (7), and (8) indicate that discomfort glare is dependent on the intensity, on the intrinsic brightness, and on the area of the glaring sources, and that this dependence can be expressed by a single equation:—

$$B_b = \gamma \frac{I^{1.3}}{A^{0.3}} \quad \ldots\ldots\ldots\ldots (9)$$

On the basis of one chance in five of error the index to I can be taken as 1.3 ± 0.12, and the index to A as the index to I less 1.

γ in the expression above is a constant depending upon the geometry of the installation and upon the degree of glare. All the measurements of Section 8, ii (a)—(c) were made upon an installation of the same geometry. The mean values of γ were then as follows:—

Criterion A (just intolerable), $\gamma = 0.9 \times 10^{-5}$
„ B (just uncomfortable), $\gamma = 4.02 \times 10^{-5}$
„ C (satisfactory), $\gamma = 16 \times 10^{-5}$
„ D (just not perceptible), $\gamma = 79.9 \times 10^{-5}$

There was thus an interval of approximately × 4 in brightness between the degrees of glare. For most purposes it is convenient and sufficiently accurate to assume a ratio of × 4 between the background brightnesses associated with the four degrees of glare. This ratio has been assumed and the values of the constant adjusted to the following:—

A, $\gamma = 1.1 \times 10^{-5}$
B, $\gamma = 4.2 \times 10^{-5}$
C, $\gamma = 16.8 \times 10^{-5}$
D, $\gamma = 67 \times 10^{-5}$

These were taken as the mean values in subsequent calculations.

The probable accuracy in these values of γ can be expressed in terms of the standard deviation of the mean readings of individual observers from the true mean (see page 9). Based on one chance in five of error, therefore, the probable accuracy is ± 30 per cent. approximately.

(d) Readings were made by two observers employing a photograph on which one source only was

exposed, of angular distance 5° from the point in the carriageway, 300 ft. from the observer.

Each observer made three complete sets of readings in order to obtain directly the relationship between background brightness, source intensity, and source area for this one source. Readings obtained by one observer are shown in Fig. 16. The

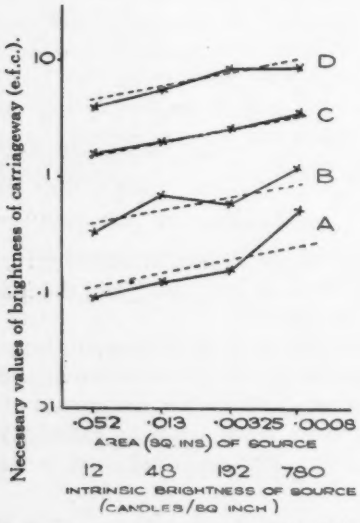

Fig. 16 (*a*). Relation between background brightness of carriageway and source area and intrinsic brightness for constant intensity. Readings of one observer. One source only exposed.

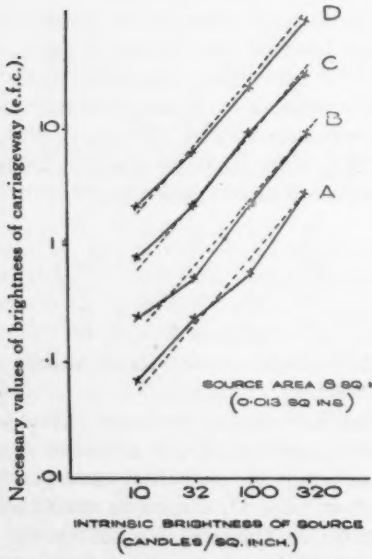

Fig. 16 (*b*). Relation between background brightness and source intrinsic brightness and intensity for constant source area. Readings of one observer. One source only exposed.

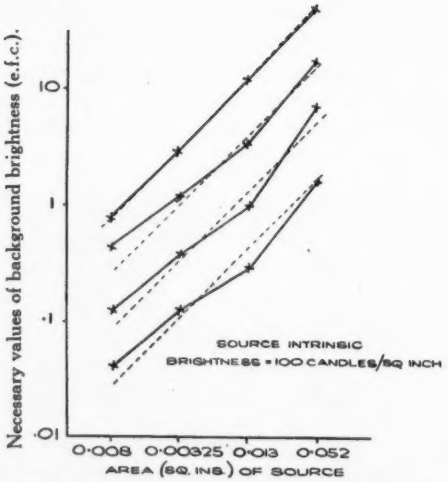

Fig. 16 (*c*). Relation between background brightness and source area and intensity for constant source intrinsic brightness. Readings of one observer. One source only exposed.

readings obtained by the second observer followed the same lines and were of the same order as those of the first observer and are therefore not shown for lack of space.

It was found that if the source area were retained constant and the source intensity varied by changing the source intrinsic brightness then:—

$$B_b \propto I^{1.15} \text{ for observer A.}$$

$$B_b \propto I^{1.44} \text{ for observer B.}$$

If the source intrinsic brightness were retained constant, and the source intensity varied by changing the area of the source, then:—

$$B_b \propto I \text{ (for both observers).}$$

If the source intensity were retained constant by increasing the source brightness with a reciprocal decrease in source area, then:—

$$B_b \propto \frac{I}{A^{0.15}} \text{ for observer A.}$$

$$B_b \propto \frac{I}{A^{0.5}} \text{ for observer B.}$$

These readings confirmed that the same type of relationship,

$$B_b = \rho \frac{I^x}{A^{x-1}}$$

held for the condition of one source exposed as for a complete installation.

(iii) Additive Nature of Glare Effects.

(a) Readings were made by seven observers, all of whom were research engineers engaged on street

lighting or other problems of vision. The "standard" photograph (see page 12) was employed. The observers first made, as usual, a short series of measurements under the standard conditions (see page 12) from which were obtained the values of general background (road) brightness corresponding to values of source intensity for equal degrees of glare. The observer next made a series of observations, for which only one source of the installation was exposed at a time. With one source in the field of view the observer adjusted the background brightness to such values that, in turn, the four degrees of glare were given by that source. This was repeated for each source of the installation. Those values of road brightness with which each source produced a given degree of glare were then added together and compared with the value of road brightness with which the complete installation produced the same degree of glare.

This procedure was repeated at other levels of source intensity.

TABLE VII.

Readings of brightness of carriageway (e.f.c.) for four degrees of glare given by (a) one source of an installation at a time, and (b) by the complete installation.

Source No.	Glare source intensity = 1,000 candles. Degree of glare.				Glare source intensity = 10,000 candles. Degree of glare.			
	A	B	C	D	A	B	C	D
(150 ft.) 1	0.007	0.022	0.12	0.28	0.07	0.2	0.8	3.5
(300 ft.) 2	0.007	0.016	0.07	0.24	0.05	0.16	0.5	2.5
(450 ft.) 3	0.005	0.013	0.04	0.18	0.05	0.11	0.37	2.5
(600 ft.) 4	0.003	0.007	0.022	0.15	0.03	0.09	0.27	1.5
(750 ft.) 5	0.003	0.005	0.011	0.04	0.02	0.05	0.17	0.8
Σ1—5	0.025	0.06	0.26	0.89	0.22	0.61	2.1	10.8
Readings on complete inst'llation	0.022	0.07	0.24	0.85	0.25	0.5	3.0	7.2

Table VII. gives results obtained by one observer. In this table the values obtained by addition of the individual readings for each single source are compared with the readings made when the complete installation was exposed. The agreement is seen to be close.

These results are typical of the whole group of observations, and only in the case of one observer was the discrepancy between the added and the directly measured values greater than the experimental tolerance.

(b) Readings were made by three observers, another copy of the same standard representation photograph being employed. This photograph was supplied with seven identical source apertures of diameter 2 mm. disposed round a circle whose centre was at the centre of perspective of the photograph and whose radius corresponded to a separation of 5° from the centre of the circle. These seven sources were arranged at intervals of 30° round this circle (see Fig. 17).

The observer, fixing his gaze on the centre of the circle, adjusted the road brightness to give, in turn, each of the four degrees of glare, all seven sources

Fig. 17. Standard representation photograph with sources disposed round a semicircle of 5° radius.

being exposed together. This procedure was then repeated, only one source being exposed at a time. (It is important to note, in view of later interpretations of this experiment (Appendix III.), that all through the experiment the observer fixated on the centre of the circle of sources.)

Readings obtained by one observer are tabulated in Table VIII. (See page 18.)

The results again showed that the sum of the values of general background (road brightness) with which a certain degree of glare is given by each of a number of sources exposed separately approximates closely to the value of background brightness with which the same degree of glare is given by all the sources exposed together.

(iv) Effect of the Position of the Sources in the Field of View.

(a) Another exact copy of the standard representation photograph was supplied with twelve identical sources, disposed at intervals of 1° from the fixation

TABLE VIII.

Readings of brightness of carriageway (e.f.c.) for four degrees of glare given by (a) one of seven sources separated 5° from fixation point, and (b) by all seven sources.

Separation of each source = 5° from fixation point.					
Source No.	ϕ see Fig. 17	Degree of glare.			
		A	B	C	D
1	90° L	0.28	0.8	1.8	5.1
2	60° L	0.37	0.91	2.0	4.2
3	30° L	0.32	1.02	3.0	6.1
4	0°	0.32	1.02	3.0	7.9
5	30° R	0.24	0.6	1.4	3.7
6	60° R	0.28	0.7	2.0	4.4
7	90° R	0.32	0.91	2.4	5.1
Σ1—7		2.13	6.0	15.6	36.5
Readings made with all 7 sources exposed (mean of 2 readings).		1.85	4.5	12.5	43

point, in a vertical line passing through the fixation point (see Fig. 18). Each source was of the same area and intrinsic brightness, producing the same illumination on the eye.

The observer adjusted the general background brightness to give, in turn, each of the four degrees of glare, one source at a time being exposed. The order in which the sources were exposed was chosen at random.

The results obtained in this way showed that the

Fig. 18. Standard representation photograph with sources disposed at intervals of 1° above the centre of perspective.

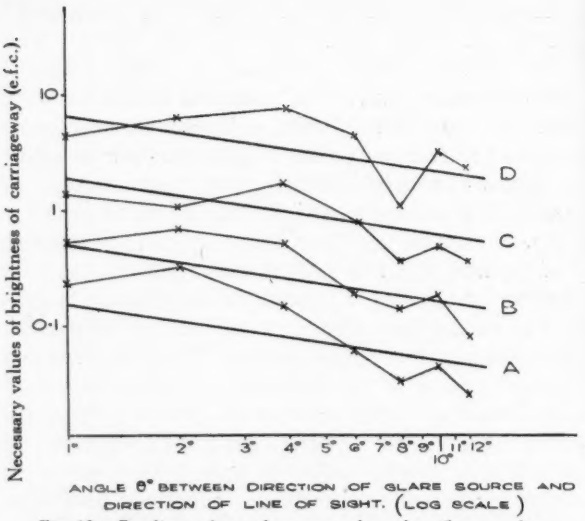

Fig. 19. Readings of one observer to show the effect on glare of the angle between the direction of the source and of the line of sight. The mean curves shown are derived from a large amount of other data not shown above.

greater the angular separation of the glare source from the fixation point the less the glare effect of the source. Observers differed somewhat in the magnitude of this decrease in glare. Fig. 19 shows the plotted readings obtained by one observer at one value of glare source intensity. Similar series of readings were obtained at other intensity levels, but are not shown here, in order to avoid confusion.

It was found, in every case, that mean curves following the expression

$$\log B_b = -n \log \theta + h, \text{ i.e. } B_b \propto \frac{1}{\theta^n}$$

could be drawn to fit the observations closely for values of θ between 1° and 12°.

The seven observers who made readings gave values of n varying from 0.5 to 1.0, the mean of the values being 0.75. It was not possible within the scope of the investigations to obtain readings from a greater number of observers, because the measurements, which involved the task of estimating the glare from one source only, were very difficult even to skilled observers. A number of cross-checks and indirect determinations were made by these observers, which confirmed the individual values of the index n for each observer. This mean value of n=0.75 was therefore accepted with the reservations necessary in view of the small number of observers making the measurements and also in view of the spread between observers of the value of n.

In view of the small number of observers a statistical analysis of the results was not of great value.

The mean value of the index n was 0.75, and the standard deviation 0.175. This deviation was greater than would have been expected to be due only to chance, and there was an indication that the spread of the readings was due to some real difference in the vision of the observers concerned with the measurements.

(v) INTER-CHECK EXPERIMENTS.

The experimental work described above led to an empirical expression, which summarises the correlation between the various physical factors which affect discomfort glare. This expression was of the form

$$B_b = c \Sigma \frac{I^{1.3}}{A^{0.3} \theta^{0.75} d^2} \text{ (See page 6)} \ldots\ldots\ldots\ldots (5)$$

This expression was tested in its application to various problems by a number of check experiments.

(a) *The effect of mounting height of the sources of an installation on discomfort glare.*

Since the discomfort glare caused by a single source is dependent upon the angular separation of the direction of the source from the line of sight, it follows that the mounting height of the sources of an installation must also affect the degree of glare.

The effect of mounting height can be studied by calculating the background brightness (for a given degree of glare) for installations of different mounting height, using the expression given above, the appropriate value of θ being substituted in the case of each source of each installation.

A large number of experiments was performed to check this calculated effect against actual measurement. A photograph, an exact copy of the standard representation photograph previously used, was employed, and which was furnished with a brass slide in which were drilled a number of apertures corresponding to the sources of installations of 30, 25, 20, 15, and 10 ft. mounting height. Each of these installations could, in turn, be presented to the observer.

The data thus obtained confirmed the calculations, provided that the value of θ, which was substituted in the expression for B_b above, was that measured from the centre of the source to the nearest point of the carriageway. (Appendix III.)

(b) *Relative glare effect of each source of an installation.*

The relative glare effect of each source of an installation cannot be assessed except by some method of mental estimation. Some indication of the relative effect can be obtained from the different values of background brightness with which each source of an installation produces the same given degree of glare. Such values were determined by seven observers for the case of an installation of 25 ft. mounting height, 150 ft. staggered spacing, of equal intensities for each source, the observer being 150 ft. from the first post (Experiment (iii) (a) above). These values were checked by calculation from the empirical expression

$$B_b = c \frac{I^{1.3}}{A^{0.3} \theta^{0.75} d^2} \ldots\ldots\ldots\ldots\ldots (3)$$

The agreement between the measured and calculated values was within the limits of the experimental error.

An indication of the relative glare effect of each source of an installation employing light distributions A, B, or C (Fig. 10) is given by the values of B_b tabulated against each source in Table XIII. (columns 10, 11, and 12). Note that B_b for the first source is, in the case of distribution A, rather greater than one half B_b for the whole installation, and, in the case of distribution B, four-fifths of B_b for the whole installation. For these particular distributions the first source is thus responsible for a large proportion of the total *discomfort* glare.

(c) *Relative glare effect of staggered (diagonal) central, single-side left, single-side right, and double (opposite) arrangements of sources.*

Readings were made, by one observer only, employing an exact copy of the standard representation photograph previously used. This photograph was fitted with a means of changing the arrangement of the sources with the minimum of delay. Details of the experiments conducted need not be amplified.

The results, however, indicated that a central and a single-side left arrangement were most glaring, and single-side right and staggered arrangements less glaring, *for given values of source intensity and background (road) brightness.* Under conditions of actual practice, the background brightness would be determined by many factors which must be taken into account when applying this result.

The results agreed with the order calculated from the empirical expression above in which the various arrangements would be expected to be placed for glaring effect, but the magnitude of the differences between the different arrangements, as measured, was rather greater than was indicated by calculation from the empirical expression, although within the margin of experimental error.

(d) *Effect of adding sources to an installation (by decreasing spacing, adding extra rows of sources, etc.)*

Tests were made, employing the same apparatus as for Experiment (v) c, to determine the effect upon

glare of increasing the number of sources in the field of view. These tests, which followed the same lines as previous experiments, involved the measurement of background (road) brightness for a given degree of glare, under various conditions of installation arrangement, with different spacings, and different numbers of sources. The results so obtained agreed with calculation from the empirical expression, within the limits of the experimental error.

(e) *Glare from one large source compared with glare from several small sources of the same total intensity.*

The apparatus of Experiments (ii) (a) and (iii) (b) was employed. Three observers took part. The observer was first confronted with the photograph of Experiment (ii) (a), which was arranged to show one source only, separated 5° from a fixation point which was defined to the observer. The area of this source was adjusted to 22.0 sq.mm. The intrinsic brightness of the source was adjusted to 100 candles/sq. inch. The observer set the background (road) brightness such that, in turn, this one source gave each of the four degrees of glare.

This was repeated with seven sources exposed, the total area of these being equal to that of the one source; the readings obtained are given in Table IX.

TABLE IX.

Readings of brightness of carriageway (e.f.c.) for four degrees of glare given (a) by seven sources, each of area 3.14 sq. mm., disposed round a semicircle of radius 5°, (b) by seven sources each of area 3.14 sq. mm., disposed round a quarter-circle of radius 5°, and (c) by one source of area 7 × 3.14 = 22 sq. mm., separated 5° from the fixation point.

Intrinsic brightness of sources = 100 candles/sq. in. Figures are the mean of three readings.

	Observer I				Observer II				Observer III			
	Degree of Glare				Degree of Glare				Degree of Glare			
	A	B	C	D	A	B	C	D	A	B	C	D
(a) With seven sources disposed round semicircle	1.1	2.6	15	40	1.9	4.5	12.5	43	-	-	-	-
(b) With seven sources disposed round quarter-circle	0.9	2.5	7.5	54	1.5	6.4	14	41.5	1.5	3.9	11	39.5
(c) With one source	1.0	2.4	8.1	43	1.3	5.9	21	44.5	1.2	4.6	13	36

The results indicated that there appears to be no consistent difference between the glare effect of several small sources and one large source of the same total intensity, provided the intrinsic brightness remains constant and the angle separating the glare source or sources from the fixation point of the eye is unaltered.

(vi) Check With Existing Installations.

From time to time as the investigation proceeded, estimations were made by a number of observers of the discomfort glare in existing street lighting installations. These observers were well acquainted with the four criteria of discomfort glare and had made several series of determinations on the laboratory apparatus.

Each observer separately gave his opinion of the glare obtaining in each street, in terms of the four degrees of glare (A = just intolerable, B = just uncomfortable, C = satisfactory, D = just not perceptible), which had been defined for the laboratory investigation. These four degrees were, of course, in the nature of changeover points easily recognised when the conditions of the installation are variable, but occurring only fortuitously in actual practice. Intermediate conditions were denoted by a + or − sign when recording opinions.

A typical table of results is given below (Table X).

TABLE X.

Installation	Calculated glare	Observers' Opinions				
		Observer I	Observer II	Observer III	Observer IV	Observer V
(1)	C	C	C	C−	C	C−
(2)	C	C	C	C−	C	C−
(3)	B	B+	B+	B	B+	B
(4)	B+	B+	B+	B+	B+	B

+ indicates less glaring, − indicates more glaring.

The constants of each installation (source intensity, flashed area of source, spacing, etc.) were measured if not already known, the road brightness measured, and hence the degree of glare which would be expected from consideration of the empirical expression obtained in the laboratory was estimated. The agreement between laboratory and field measurements was usually very close. There was never a discrepancy as much as one degree of discomfort.

The checks which were made in this way from time to time indicated that the results of the laboratory investigations could be interpreted

quantitatively in relation to problems of actual practice, without the need for a correction factor.

(vii) Relative Glare Effect of White, Bluish, and Yellowish Light.

The check readings reported in the last section were made on installations of incandescent tungsten, incandescent gas, mercury vapour electric discharge and sodium electric discharge lamps. No regular measurable distinction in relative discomfort glare, as distinct from pleasing appearance, between the four types of light source was detectable from the readings. It was a matter of considerable difficulty to equip the model street glare apparatus with provision for examining the effect of all four sources of light. It was thought, however, that if any appreciable difference existed there should also be some measurable difference between the glaring effects of white (incandescent tungsten) light, bluish light, and yellowish light, the two latter being obtained by appropriate filters from tungsten light to give a colour match with high pressure mercury vapour discharge and sodium discharge light respectively.

The model apparatus was, therefore, provided with a means for sliding blue and yellow filters into position over the glare sources of the standard representation photograph and over the picture illuminating lamps. Observers adjusted the road brightness on the model to the standard four degrees of glare for blue, yellow, and white light in turn, with various values of source intensity.

A series of results is plotted in Fig. 20. The results showed that there is no difference in glaring effect of white, bluish, or yellowish light that can be detected by the method employed.

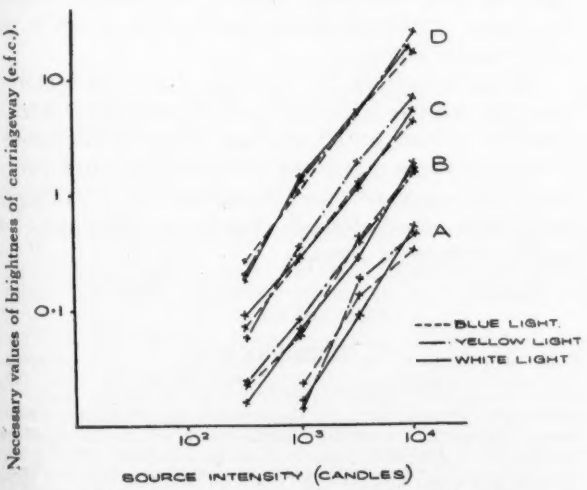

Fig. 20. Relative glaring effects of yellowish, bluish, and white light.

(viii) Effect of Change of Sky and Surround Brightness upon the Discomfort Glare from the Sources of an Installation.

Estimations of glare in actual installations when compared with calculation from the empirical expression (page 6) indicated that in certain cases an installation, which would have been expected to be uncomfortably glaring, was actually not so because the presence of light coloured buildings increased the general surround brightness level sufficiently to modify the discomfort caused by the sources. Conversely, an installation in an arterial road with no surrounding background appeared rather more glaring than would have been expected by calculation from the expression obtained from laboratory measurements.

The magnitude of the effect upon glare of such changes in background brightness was investigated in the model apparatus. Three series of estimations were made, employing the "standard" photograph (see page 12), (a) with the photograph unaltered, (b) with a black velvet surround (reflection factor less than 1%) substituted for the sky and building area of the photograph, and (c) with a light grey surround (reflection factor 20%) substituted for the sky and building area of the photograph. The readings (of one observer only) indicated that the effect of a black surround to the roadway is to increase glare considerably (see Fig. 21), whilst the effect of a light grey surround is to reduce the glare slightly when compared with the normal surround of trees and a few buildings which is fairly general on suburban traffic routes.

The conditions of experiment are, however, without doubt, more severe than those likely to be experienced in practice on the open highway, because in practice the effects of atmospheric scatter tend to produce a higher surround brightness relative to the road brightness than that represented by the brightness of the black velvet of the experiment. Estimations on arterial roads indicate, however, that the brightness of the carriageway of an arterial road should certainly be approximately twice that on a normal traffic route with surrounding trees, buildings, etc., for the same degree of discomfort glare.

(ix) The Effect of Pre-Adaptation of the Eye upon the Degree of Discomfort Glare.

In passing from a poorly lighted street, one is often more conscious of the discomfort caused by glare

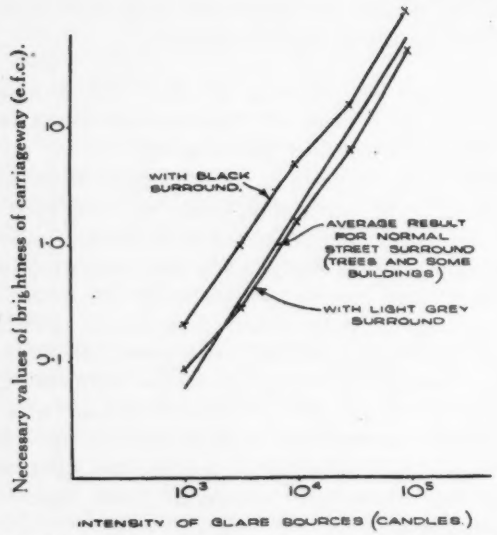

Fig. 21. Effect upon necessary values of road brightness for given degree of glare of black and of grey surrounds. Criterion B (just comfortable) shown only.

from the sources of the well-lighted street than after some time has been spent in the installation. The reverse also is true, i.e., one is less distracted by the sources of a poor installation when still adapted to a higher level of brightness.

A series of experiments made on the model street apparatus, employing the "standard" picture, confirmed this effect, showing, as would be expected, that the light-adapted eye is less sensitive to glare than is the dark-adapted eye.

No further experiments were made on the effect upon discomfort glare of pre-adaptation of the eye.

10. Comparison with Previous Work.

Previous work on discomfort glare has been confined to conditions differing very considerably from those of street lighting practice. The work of Nutting(7) was concerned with conditions of uniform background brightness, and of one large glare source, whilst that of Luckiesh and Holladay(8) was concerned with conditions of momentary exposure of the glare source. Neither investigation was concerned with glare from a number of small sources in a non-uniform field under conditions of continuous exposure.

The criterion of "discomfort" will naturally depend upon circumstances: it is very probable that lighting which will be considered uncomfortable in one visual task will be tolerated in some different task. Similarly, the "discomfort" registered under idealised conditions in a laboratory experiment, with the observer looking at, say, a white screen, cannot necessarily be related to that experienced in practical circumstances of vision in, for example, a street. Association of ideas, and psychological factors, almost certainly play a large part in the problem, and any laboratory experiment to be valid should simulate as accurately as possible the scene and visual conditions which would be met in practice.

A direct comparison of the results obtained from the present investigation with those of previous investigations is therefore not possible.

It is of interest, however, to record here that opportunity was taken, during the course of the present investigation, to make some measurements under conditions of uniform background brightness, employing small and large glare sources. A feature of these results was that very small sources produce discomfort effects which are dependent chiefly upon the source intensity and almost independent of the source intrinsic brightness, but that as the size of the source is increased, the discomfort effects depend to an increasing degree upon the source intrinsic brightness and to a less degree upon the source intensity.

No measurements were made under conditions of momentary glare.

11. Conclusion.

Discomfort glare is only one of the problems of vision under artificial lighting conditions. Although the present work has been concerned with street lighting only, the experimental technique which has been employed could be applied directly to other conditions.

The investigation has shown that a subjective quantity, such as discomfort, can be studied quantitatively in relation to the relevant objective quantities. It is conceivable that work on other subjective problems (for example, the perception of brightness) could be attacked along similar lines, with hope of a useful measure of success.

Appendix I.

DISCOMFORT GLARE CALCULATIONS.

In order to save the time involved in applying the expression of page 12, a simplified method is given for calculating the effect of discomfort glare in an installation. This is not strictly accurate, but gives a result sufficiently close for most purposes. The principle of the simplification is to substitute, for all the sources of the installation, a single source of

(7) Trans. I.E.S. (U.S.A.), vol. 9, p. 939. (8) Trans. I.E.S. (U.S.A.), vol. 20, p. 221.

equivalent intensity, area, distance, and angular separation from the line of sight, and then to apply the empirical expression.

Method.

In the tables below, the value of each one of the factors affecting discomfort glare is tabulated with a corresponding number. The relation between these numbers is a simple arithmetic one, so that they can then be added or subtracted to obtain whichever factor is unknown.

BRIGHTNESS TABLE.

Average Road Brightness (e.f.c.)	.01	.02	.03	.05	.07	.1	.2	.3	.5	.7	1	2	3	5
Brightness number	−2	−1.7	−1.5	−1.3	−1.15	−1	−0.7	−0.5	−0.3	−0.15	0	0.3	0.5	0.7

INTENSITY TABLE.

Total Apparent Intensity (candles)	300	500	700	1000	1500	2000	3000	5000	7000	10000	15000
Intensity Number	3.24	3.51	3.7	3.9	4.02	4.3	4.55	4.81	5.0	5.2	5.42

SOURCE AREA TABLE.

Total apparent source area (sq. ins.)	10	15	20	30	50	70	100	150	200	300	500	700
Area number	.3	.35	.39	.45	.51	.56	.6	.65	.69	.74	.81	.85

SPACING TABLE.

Spacing (feet)	100	125	150	175	200	225	250
Spacing number	4	4.19	4.36	4.49	4.6	4.70	4.8

TABLE OF θ NUMBERS.

Mtg. Ht.	Spacing.				
	100′	125′	150′	175′	200′
10′	.42	.37	.27	.18	.1
15′	.53	.47	.40	.33	.24
20′	.62	.56	.50	.44	.38
25′	.68	.63	.58	.53	.49
30′	.72	.68	.63	.60	.58

Correction for road width is usually small and may be neglected.

GLARE TABLE.

Degree.	Glare number for built-up highway.	Glare number for open highway.
Just intolerable	—0.1	0.2
Just comfortable	0.5	0.8
Satisfactory	1.1	1.4
Just not perceptible	1.7	2.0

The following relationship then holds between the numbers in the above tables:—

GLARE NUMBER + INTENSITY NUMBER = BRIGHTNESS NUMBER + AREA NUMBER + θ NUMBER + SPACING NUMBER.

If any one of these factors affecting discomfort glare is unknown, the appropriate number can be quickly found in this way, and hence, from the table, the value of the factor.

When assessing the accuracy of such a calculation, it will be remembered that the primary quantity considered is discomfort glare, the estimation of which is necessarily an uncertain process. Thus it is of little moment if the simple method of calculation prescribes, for example, an installation brightness of 0.5 e.f.c., and the more exact method an installation brightness of 0.4 e.f.c. The discrepancy is less than the degree of accuracy of the experiments upon which the data for the calculation have been based.

"Total apparent intensity" is the total intensity referred to the plane of the first source of the installation. Thus the apparent intensity of the second source, twice as far away, will be one-quarter the actual intensity, the apparent intensity of the third source will be one-ninth of the actual intensity, and so on, if the spacing is regular. For speedy calculation, the relationship:—

Total apparent intensity ≅ intensity of first source + $\frac{1}{10}$ (sum of actual intensities of all subsequent sources) will be sufficiently close.

"Total apparent area" is similarly the total area of the sources referred to the plane of the first source. Similarly total apparent area ≅ area of first source + $\frac{1}{10}$ (sum of areas of all subsequent sources).

Example I.

To calculate the probable degree of glare obtaining in an installation of ten sources, spaced 150 ft. apart diagonally, mounting height 25 ft., source area 100 sq. in., intensities as given by distribution B (page 11), the road brightness being 0.5 e.f.c. approximately.

Total apparent intensity ≅ 3200 + $\frac{1}{10}$ (1750+1000+950+900 +850+800+700+600+500)
≅ 4005

Total apparent area ≅ 100 + $\frac{1}{10}$ (9×100)
≅ 190

Brightness number ... = −0.3 (B = 0.5 e.f.c.)
Intensity number ..... = 4.7
Area number ..... = 0.68
Spacing number..... = 4.36
θ number..... = 0.58
∴ glare number ..... = −0.3 + 4.36 + 0.68 + 0.58 − 4.70
= 0.62

Since "just uncomfortable" corresponds to glare number 0.5, and "satisfactory," or "just not distracting," to 1.1, the glare will not be uncomfortable, but will certainly be distracting.

Example II.

To calculate the source area of lanterns to be substituted for an installation which now gives uncomfortable glare, in order that the glare may be "satisfactory." The average road brightness is 0.5 e.f.c., the spacing 100 ft. double, mounting height 15 ft., and the intensity of each of the twelve sources is 500 candles.

Total apparent intensity ≅ (500 + $\frac{1}{10}$ (5 × 500)) × 2 for double row of sources.
≅ 750×2
≅ 1500

Intensity number ..... = 4.02
Brightness number ..... = −0.3
Spacing number ..... = 4.0
θ number ..... = 0.53
Glare number ..... = 1.1 (satisfactory).
Then area number = 1.1 + 4.02 + 0.3 − 4.0 − 0.53
= 0.89
∴ total apparent area (from area table)
= 900 approximately.

If all the sources have the same actual area, then
900 = 2 (A + $\frac{1}{10}$ (5A)) for a double row
= 3A
A = 300 sq. in.

∴ the sources should have a flashed area of approximately 200-500 sq. in., if the degree of glare is to be "satisfactory."

Appendix II.

MEASUREMENT OF THE INTENSITIES OF THE GLARE SOURCES OF AN INSTALLATION.

The measurement of the intensities of each of the sources of an existing installation is a laborious process if the light distribution is not known. If, however, a high degree of accuracy is not required, the "total apparent intensity" of all the sources (see Appendix I.) can be found by measuring the illumination produced on a vertical plane at the observer's eye, when he is standing under a post, i.e., he is distant from the first post in his field of vision by the spacing distance, and by multiplying this value by the square of the distance of the first post from the observer. The calculation of Appendix I. can then be proceeded with.

If, however, the light distribution of the sources is known, the intensity of each source can be found from a photograph of the installation by the method described on page 3.

Appendix III.

MEASUREMENT OF θ, THE ANGLE OF SEPARATION OF A GLARE SOURCE FROM THE LINE OF SIGHT.

It was found, when conducting the experiments of Section 8, vi (a), on the effect of mounting height, that the substitution in the expression

$$B_b = c \Sigma \frac{I^{1.3}}{A^{0.3} \theta^{0.75} d^2}$$

of values of θ measured from the main "attention" point (Fig. 1) led to a calculated effect of mounting height which differed somewhat from the experimental results. Although this difference was small, and not of great significance, it was consistent and was therefore investigated in some detail. The experimental results indicated that the term $\frac{1}{\theta^{0.75}}$ in the empirical expression did not fully compensate for the effect of the approach of the sources to the line of sight when the mounting height was reduced. This could be due to two causes, either that (a) the index to the θ term was incorrect, or that (b) the values of θ as measured from the point 300 ft. away on the carriageway did not truly measure the angle between the direction of the source and the line of sight.

The slope of the measured curves would have indicated a value of about 1.5 for the index to the θ term, if (a) above were the reason for the discrepancy. Repeat determinations of the index to the θ term were made, using the data of experiment (iv) above: the previous values of the index, i.e., between 0.5 and 1.0, were confirmed.

Although the point 300 ft. away on the carriageway is described by a majority opinion as the point at which a car-driver would concentrate most of his attention when driving down a straight road, drivers have, however, noticed that they also allow their gaze to wander slightly in order to scan the pathways and kerb-sides for likely obstructions moving into the roadway. Consequently it would be expected that a low-mounted source, being nearer to the boundaries of the area which the observer would scan for the presence of obstructions, would cause more distraction than another source, mounted higher, although separated from the main "attention" point by the same angular distance as the first source. This effect should be especially noticeable under the conditions of Experiment (iii) b, in which seven sources are disposed round a semicircle with its centre at the centre of perspective approximately 1° vertically above the "attention" point. (See Fig. 17.) The sources on the horizontal diameter of the semicircle are much closer to the road and pavement than the source on the vertical diameter. The readings obtained during the course of Experiment (iii) b showed that when the observer fixated, each of the seven sources produced the same glare effect, within the limits of error of the experimental procedure. This experiment was repeated, but the observer did not fixate any one point. It was then found that the sources nearer to the carriageway caused more discomfort. Figure 22 shows the result of plotting these measurements together with those obtained from Experiment iii (b) (Table IX). Although the spread of results is in both cases very large, there is a definite increase in the discomfort glare from the sources near the carriageway when the observer does not fixate, as evidenced by the increased values of background brightness necessary in order that the sources may not give more discomfort than the sources vertically above the carriageway.

The averaged results of all the observations made showed that a much more accurate expression of θ is obtained, in the case of a lighted street, if θ is measured from the centroid of the source to the nearest point of the carriageway (pathway included); this is because the observer's line of sight is not fixed, but changes as the observer scans the roadway and its vicinity for possible obstacles.

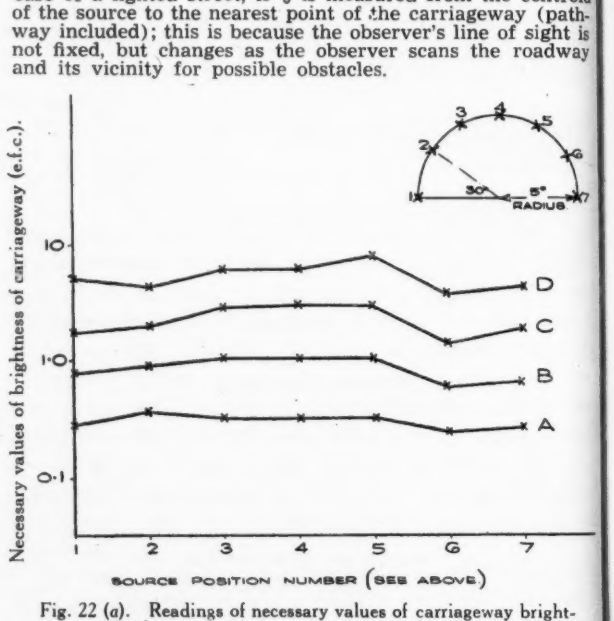

Fig. 22 (*a*). Readings of necessary values of carriageway brightness such that each of four degrees of glare are given by sources spaced round a semicircle, the observer fixating the centre of the circle.

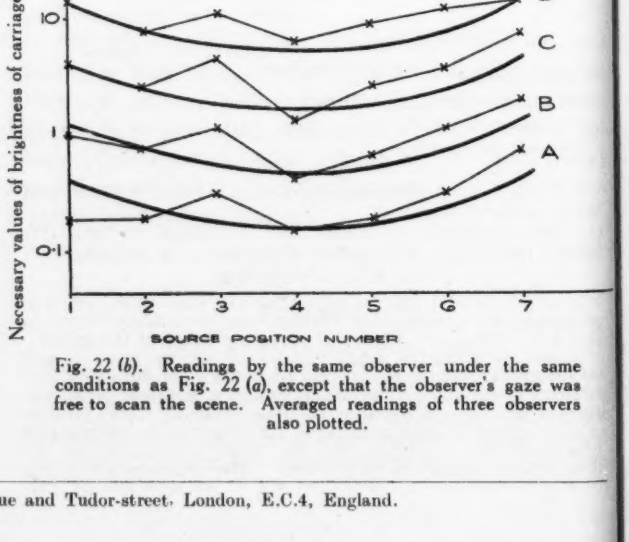

Fig. 22 (*b*). Readings by the same observer under the same conditions as Fig. 22 (*a*), except that the observer's gaze was free to scan the scene. Averaged readings of three observers also plotted.

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DISCOMFORT GLARE IN LIGHTED STREETS

(Discussion of the paper on the above subject read by Mr. R. G. Hopkinson, on January 9th, 1940.)

Dr. W. S. STILES, congratulating the author on having reduced the elusive subject of discomfort glare to quantitative terms, said that one of the great difficulties about discomfort glare was that it could not easily be fitted into our scheme of knowledge about the properties of the eye. Therefore the author had been wise not to attempt to theorise about the results he had obtained but to concentrate on showing that he could "measure" discomfort glare in some way. Mention had, however, been made of the so-called "general adaptation level" in giving a simple picture of the mode of origin of the discomfort caused by a glare source. In this connection there was another factor which was of importance, viz., fixation. If we could maintain our fixation perfectly so that every part of the retina of the eye became adapted to the brightness which was falling upon it, including the parts covered by the images of the glare sources, it might then be expected that any discomfort due to lack of adaptation would disappear. In practice it was not possible to maintain perfect fixation. The eye must make certain movements which would disturb the adaptation. Thus eye motions were probably of great importance in discomfort glare. In that connection it would be interesting to know whether the observers confined their attention to one part of the field or whether their eyes were allowed to wander.

Continuing, Dr. Stiles said the crux of the paper was the criterion for discomfort, and having had the privilege of seeing the full paper he felt that the author had undoubtedly established that there was something reproducible in the observer's judgments about discomfort glare and that different observers had some conformity of viewpoint. That was a most interesting piece of information. It was hard to say whether these judgments corresponded to the discomfort actually experienced in practice.

Would it have been possible for the observers to have been given some simple task, such as reading very large letters to keep them occupied, and then to have reported on the degree of comfort or discomfort after a certain period? This was a method which had been used, and which had some advantages.

The formula which the author had put forward was very interesting but it was impossible properly to comment on its implications at present. However, it would be noticed that in the formula there was no reference to the background against which the glare sources were viewed. In these experiments he imagined that the brightness against which the glare source was seen was proportional to the brightness at which the observer was looking. If the author had varied independently these two brightnesses he might well have found that both required a place in the formula.

The author had distinguished between four degrees of discomfort glare, whereas Holladay, in an investigation of some years back, had worked with twelve degrees. He (the speaker) had been rather sceptical of Holladay's work on these lines because of the fine distinctions drawn between different degrees of discomfort glare. The same objection did not apply to the author's inyestigation. Owing to the many differences between the experimental arrangements, a close comparison of Holladay's formulae with the author's formula could not be made. It was to be hoped, however, that confirmation of the main points in the author's results would be obtained in an independent investigation.

The following communication from Dr. W. D. Wright was then presented.

Dr. W. D. WRIGHT (Communicated): I am particularly interested in the physiological processes responsible for glare effects, and a number of interesting points arise from Mr. Hopkinson's paper. The troubles due to glare must largely arise from two causes (1) scattering in the media of the eye, and (2) the fact that the nerve response from those points of the retina at which the glare sources are imaged is considerably higher than the response from the rest of the retina. The former produces a veiling action that is rightly regarded as a disability effect whose magnitude has been determined from experiments on thresholds and is included in the Holladay-Stiles expression for disability glare. The latter produces an inhibitory reaction which tends to reduce the response from other parts of the retina and is, presumably, also included in the effects described by the Holladay-Stiles expression. In addition, it causes the discomfort effect that Mr. Hop-

kinson has measured. It is probably true, therefore, to say that the discomfort glare and part of the disability glare arise from the same cause, but that part of the disability glare, that due to the scattering, plays no part in producing discomfort.

This will largely account for the difference between the law found by Mr. Hopkinson for discomfort glare and that given in the Holladay-Stiles expression for disability glare. The difference between the two expressions includes both the effect of varying the intensity of the glare source and that of varying the angle between the glare source and the test surface. A further cause for the difference may be that the Holladay-Stiles expression is based on threshold test brightnesses, while in Mr. Hopkinson's experiments the road surfaces were, I imagine, well above threshold. In binocular matching experiments which I have carried out recently I have found a very large difference in the inhibitory effect of a glare source, depending on whether a high or a low intensity test object was used. It may be that, when the inhibitory action of a glare source has been determined for various conditions of glare, using a test surface of appreciable brightness, a relation may be obtained similar to that obtained by Mr. Hopkinson for discomfort glare. If so, an alternative method for estimating discomfort glare would become available. I certainly regard it as very probable that the discomfort effect and the inhibitory action must both be intimately related to the apparent brightness of the glare sources, and that the magnitude of the one is likely to be closely related to that of the other.

Both from the theoretical and practical point of view it would be useful to know the limits for B_s, ω and θ, within which Mr. Hopkinson's law holds. At very small values of ω, for instance, it might be anticipated that the glare would depend directly on the product $B_s.\omega$ and not $B_s^{1.3}.\omega$.

The additive nature of individual glare effects is of considerable theoretical interest, and is probably in part, at least, associated with V. Kries's "Law of Coefficients."

I should like to ask Mr. Hopkinson whether he found any striking individual differences among his observers, or whether there was only a normal scattering among his results.

Mr. L. T. Minchin asked whether the author had found that, for example, it was usually the second or third lamp of a series in a street which gave the most discomfort glare, or was it impossible to answer such a question in view of the wide diversity of height, spacing, and arrangement of lamps and of the light distribution from them?

Mr. A. E. Jepson inquired whether any of the observers were wearing glasses when making their observations. He mentioned that glare was much reduced if one wore certain forms of glasses, as he had been recommended by his doctor to do.

Mr. M. G. Bennett said he gathered from the paper that in a given set of conditions, if the road brightness and glare source were increased in the same ratio, the glare, as defined in the paper, became greater. He said that he had gained the impression that, at the much lower levels of illumination used in war, the reverse was true—that is, that when everything is scaled down the glare becomes worse. He appreciated that such levels of illumination were outside the limits of the author's experiments, but wondered whether the impression was a general one.

Mr. J. A. Prowse asked if there was any lower limit of the angle subtended by the light source at which the glare was independent of the size of the source, i.e., were there any circumstances in which the glare depended solely on the total candles emitted in the direction of the observer's eye and was independent of the brightness?

Mr. J. S. Dow said that Mr. Hopkinson's researches seemed to support the belief that various factors, regarded as of minor importance in relation to disability glare, had a material influence on discomfort. It was evident, for example, from his results that the *brightness* of the lighting unit did definitely influence discomfort glare. Taking a general survey of glare in all its aspects, he had never been able to accept the view (at one time suggested as a basis for the assessment of glare in connection with the street lighting specification) that candle-power was the determining factor and brightness of no account. In his experience there was a great difference in the effect of a given candle-power derived from a bare filament as compared with a source in an opal globe of similar power. To him, Mr. Hopkinson's demonstration was instructive in this respect.

There were many different sensations and impressions, not entirely classified either under disability glare or discomfort glare, that affect judgments of conditions in the streets. The criteria at the moment were unusual. One usually saw an obstacle as a darkish mass of indistinct contour. It was appreciation of contrast rather than recognition of outline that enabled one to detect the presence of an obstacle

—and the power of perceiving barely evident contrast was easily impaired by glare. Whenever one met a case of " reversed contrast," i.e., when the area one inspected was decidedly darker than the main surround—for example, when one looked into the outside gloom, from within the dimly lighted entrance to a Tube station—one's powers of perception were impaired. In a minor degree the same thing might happen if one looked at a photograph, somewhat dark in tone, with an extensive white frame. Such effects did not involve positive discomfort, and he doubted whether they would be recognised by the usual tests of disability glare. Yet they might be all-important at a moment of danger in the dark streets—and the same applies to the momentary distraction due to catching sight of some object of relatively low brightness " out of the tail of the eye."

There was one conclusion of Mr. Hopkinson's—that the discomfort effect of individual sources was additive—which seemed to establish an important principle. For it might well result that the aggregate effect of a considerable number of identical lighting units was distressing when they were erected as an installation, even though one could not see anything amiss when one examined a single specimen.

Mr. H. S. ALLPRESS suggested that the author might try to compress some of his main conclusions into short and simple phrases or formulae, so that they could be more readily memorised and applied in practice. Mr. Dow's remarks had reminded him of the simple basic principle maintained by Bordoni, that glare was independent of brightness, provided the diameter of the light source did not exceed several hundredths of the distance of the source from the eye of the observer. This was at least a comprehensible and simple declaration. It would be helpful if Mr. Hopkinson's formula could be translated into some equally simple broad rules.

It appeared that the author's conclusions were not based primarily on theory, but were the result of a large number of practical experiments conducted with actual models of street lighting installations. From these experiments inferences in regard to the effect of brightness and candle-power, height and spacing, etc., were drawn. In a sense that was an advantage in suggesting that results should conform with practice, but there was the possibility that they would be influenced by the particular conditions under which the experiments were made and might therefore be of less universal application than if based on fundamental principles.

Mr. Allpress felt that quite possibly the results would be very largely affected by the particular types of figures used for the experiments. In effect, deduction from his results obtained with samples might show only the different degrees of visibility obtained by changing the lamp size in the particular installations with which the experiments were concerned. It was not possible to vary road brightness or other factors simply by changing the candle-power of the lamp, but the whole height and spacing arrangement of the installation would probably have to be varied to obtain a new illumination. It would appear, therefore, that results dependent upon fundamental theory might be more reliable than those obtained from experiment with samples of particular types of installations.

Finally, Mr. Allpress inquired how far Mr. Hopkinson's formula could be applied to the low intensities, which were approximately street lighting values, covered by what is meant by the present-day A.R.P. lighting. For instance, the degree of visibility obtained with 0.002 ft.c., using a standard fitting at 10 ft. high, was probably lower than that obtained with the same illumination using the same standard fitting designed for 20 ft. mounting height. The difference was probably more marked in the case of the 0.02 ft.c. unit. If Mr. Hopkinson's paper would throw any light on the most effective illumination to use in order to provide the best disclosing power, it would be of great value and it might then appear that certain A.R.P. fittings were invalidated owing to the high degree of glare associated with their design.

Mr. J. M. WALDRAM remarked that this work had kept the author and his observers looking through a hole in a little box for two years or more, and if Dr. Stiles had tried making the observations he might not have suggested that the observers should have been given some simple task as well. Mr. Dow had mentioned an important point in drawing attention to something which the author's work had underlined. In the past most attention had been paid to disability glare because it was the thing which it was first found possible to measure, but he could not help thinking that he himself, and also others, had often looked at discomfort glare while thinking of disability glare. He had been impressed with the care which it was necessary to exercise to detect disability glare. Many arguments for years past might have been due to this confusion of the two, and he felt that the author had now helped to resolve this matter. The experiments described indicated something which

was very important in experiments on lighting conditions, viz., that the experimenters should understand precisely the questions put to them and should answer only these questions. Fortunately, street lighting was a definable job, and the author had been able to approach it in a scientific way; he doubted whether discomfort in street lighting was the same thing as was known as discomfort in interior lighting.

Of all the practical factors which came out of this work possibly the connection between glare and light distribution might turn out to be one of the most important. The paper indicated that there were wide fields to explore in discovering how best to alter and vary light distribution to get the best lighting result, taking into account not only glare but all the other factors, and it was to be hoped the work which Mr. Hopkinson was doing would result in better limits being placed on glare and light distribution in order more precisely to control this difficult aspect of the work of the street lighting engineer.

Mr. A. CUNNINGTON, after congratulating the author on the excellent demonstrations he had given during the presentation of his paper, said he wished to underline the statement made towards the end of the paper that "a more closely spaced installation of sources of lower intrinsic brightness will probably be less glaring than a longer spaced installation of sources of high intrinsic brightness for a given power expenditure per unit length of road." No doubt many of them had felt that for a very long time, but they had not been able to reinforce their view with such theoretical conclusions as were to be found in this paper. The economic factor, of course, came into this, and the cost of a more closely spaced installation might be higher; but allowing for all that, he felt the aspect put forward by the author ought to be stressed. There had been too great a tendency in the past to feel that glare must be put up with, but every effort should be made to avoid glare, and it was possibly of more importance than had hitherto been attached to it. He always had had a feeling that the rigidity of the details in the British Standard Specification with regard to mounting height and spacing had tended to divert people from investigation into alternative methods, the feeling being that as the specification suggested that a 25-ft. mounting height and a 150-ft. spacing was practically ideal—according to the specification—it was not worth while to diverge very much from that. Therefore the specification rather discouraged anyone from making experiments on something which might give an entirely different distribution but which would not be eligible for a grant from the Ministry. If this were so, was it not time a change was made that would encourage the experimenter to try some alternative distribution? There might be a difference in dealing with a main street in a city or a suburban road, but it would be interesting to see experiments on an alternative method of distribution.

In demonstrating the effect of a plain lamp, an opal lamp, and a sheet of opal glass, mentioned by Mr. Dow, the author had suggested that the glare was roughly the same from all three sources, but his own impression was that the light from the large pane of glass was altogether less unpleasant than the light from the other two sources. This indicated that a large source was the crux of this matter. That had been very noticeable in blackout conditions. Recently he had been experimenting with one of the British Standard fittings for A.R.P. lighting, from which there was a rather noticeable glare owing to the very low intensity. He had found, however, that by fitting a large reflector and thus getting a very large source of light for the same illumination, discomfort glare was eliminated. The conditions, of course, were unusual and not at all the sort of thing visualised in this paper, because the background brightness was very low. However, he would like to know if this question of the size of the source of light had been taken into account. Mention had been made of the angle subtended by the source at the eye, but had the author considered unusually large angles; it seemed that the size of the source and a low intrinsic brilliancy was of very considerable importance.

The PRESIDENT remarked that although he had read the paper with some care he would have liked an opportunity to study it more thoroughly before offering any criticism. He thought the author had been very courageous in attempting to differentiate between disability and discomfort glare. Whether Mr. Hopkinson was measuring discomfort glare or something else was not quite certain at the moment, and when reading the paper he had felt considerable doubt on this point. Nevertheless, he felt convinced —as far as one could be convinced from experiments carried out on a model—that the author was measuring something which was of importance in street lighting and to that extent he had done a very useful thing. He rather felt the street lighting engineers were beginning to get a little complacent about their work and had a great deal of pride in the installations they put up. This pride was largely

justifiable. Candidly, however, his own opinion was that some installations which had been put up in recent years were not installations which engineers ought to be proud of. The lighting of dual carriageways where there were so many distracting sources presented a problem which called for study. In some installations he had seen he had been conscious of something which was distasteful and even painful.

There was one point he wished to mention, although it was not a criticism of the author's work as such. As Dr. Stiles had pointed out, the observer in these experiments was seated in a fixed position at a certain point with his viewpoint fixed. This sort of simplification was no doubt necessary in experimental work where it was always desirable to eliminate as many variables as possible at one time.

Referring to the demonstrations the author had given, when certain lamps were switched on he (the President) had experienced a distinct momentary sensation of pain—he was not exaggerating when he said pain. When one looked at an unscreened light source of high intrinsic brilliancy for a moment the reaction was distinctly painful. This kind of thing was experienced in some measure when one drove through some street lighting installations. As one drove down the street, source after source impinged on the eye momentarily and there was a definite period, although short, when one felt not only distracted but experienced pain as each of the sources came into view. He wondered whether the author had considered that kind of repetitive experience which occurred in some streets and which in his view was much more serious than some of the phenomena which the author had referred to.

Mr. A. W. Beuttell expressed the hope that the author would not overlook, in his reply, the lower limit of background brightness for which the formula in the paper could be regarded as safe. It had been stated that the formula did not apply to black-out conditions but it would be useful to have an approximate figure at which it was correct.

Mr. C. Dunbar said that he had been privileged on one or two occasions to take observations for Mr. Hopkinson, and the point which interested him greatly was the extent to which it was possible in an experiment of this type to dissociate the disability and discomfort effects of glare. It was true that the observers were instructed not to base their judgment on what they could or could not see, but he wondered whether in making this judgment the observers were able to avoid taking into account, perhaps quite sub-consciously, the visibility of certain details which would always be present in a street scene, such as the structure of the road surface, kerblines, etc. It was noticeable that in some of the installations tested by Mr. Hopkinson the answers given for discomfort glare would probably fit quite well the disability glare. Mr. Dunbar was not, of course, suggesting that the author was really measuring disability glare, but he would like to know Mr. Hopkinson's reaction to the suggestion that in spite of his precautions his formula might still include a certain amount of the disability glare effect.

Mr. R. G. Hopkinson, replying to the discussion, said that one of the main points raised was whether disability effects had not, in spite of all the precautions taken, crept into the results obtained. He believed that it was not possible at this stage to decide this point. It would be necessary to understand the physiological mechanism which caused discomfort glare. He therefore looked forward to the results of the experiments upon which Dr. Wright was engaged, because it would be from such experiments, and from the more fundamental experiments of Granit and of Hartline, that the solution to the problem would be obtained. As Dr. Stiles had pointed out, no attempt had been made to theorise about the results, but it was agreed with Dr. Wright that discomfort was most probably caused when the nerve response from the points of the retina receiving the images of the glare sources was considerably higher than from the rest of the retina. It was interesting that Dr. Wright believed that this mechanism was responsible also for part of the disability effect.

It was, however, of interest to note that if, instead of being asked to assess discomfort glare as decribed in the paper, an observer was asked to judge when an object on the road appeared just to disappear due to the disabling effect of the glare sources, a relationship differing considerably from the discomfort relationship was obtained. He, therefore, felt it was justifiable to conclude that the effect which had been investigated was indeed that effect which caused discomfort or distraction, quite apart from disability. He was not prepared to say that all disability effects had been eliminated.

He thought that it was unlikely that discomfort glare would disappear if, as Dr. Stiles had suggested, the observer fixated and allowed every part of the retina to adapt to the brightness falling upon it; this would only hold if the intrinsic brightness of the sources was comparatively low. In some cases observations had been made (see particularly

Appendix III.) which showed the difference between the discomfort glare when observers fixated and when their gaze was allowed to wander.

It had not been possible to employ a technique embodying the performance of a simple task, as Dr. Stiles had suggested, because this would have made the time taken for a series of observations very long, and observers would have become fatigued before a series could be completed.

The background brightness against which the sources are seen does contribute to the discomfort glare, and in one series of experiments (expt. 9 (viii)) the effect of a change in this background had been investigated. In any fundamental investigation this factor would have found its way into the final expression, but in this case it was considered simpler to allow for it the way that had been done in Fig. 9. The final expression which summarised the results was already complicated, and any further factor might destroy its value for direct application to problems of street lighting design. Therefore a number of second order effects which had been noted during the investigations had purposely been omitted. These included the background effect mentioned by Dr. Stiles, and also the effect, described in Section 10 of the paper, and discussed by Dr. Wright and Mr. Prowse, that the index to the term B_s in the expression depended upon the value of ω.

The limits of B_s and θ for which the expression is known to hold are:—

B_s:—1 candle/sq. inch to 1,000 candles/sq. inch.
θ :—1° to 12°.

In reply to Dr. Wright, it was found that of thirty observers tested, only two showed striking differences from the mean, and of these one (see Fig. 12) was not abnormal in his readings on actual installations. The other was apparently very sensitive to glare, his readings on the model apparatus agreeing with his readings on actual installations. This observer is known to possess particularly good night vision. The wearing of glasses did not appear to affect the susceptibility of observers to glare, and Mr. Jepson's experience was interesting in this connection.

A number of particulars of observers had been recorded, such as age, defects of vision, photometric experience, experience of night driving, etc., but sufficient observers had not been tested to make any correlation with these factors apparent.

It was of interest that both Mr. Dow and Mr. Cunnington had considered the clear lamp of the demonstration more glaring than the diffusing unit, in spite of the intensity of the diffusing unit being over four times that of the clear lamp. The majority of observers placed the sources as about equally glaring.

There was a good case for such simplification of the formula such as Mr. Allpress had suggested, because this would undoubtedly fix it better in the memory. Unfortunately there were so many variables concerned that simplification would lead to false conclusions.

For example, it could be stated that on a normal traffic route, with a semi-polished road surface, 25 ft. mounting height, 150 ft. spacing, the intensity in the direction of the eye should not exceed 3,000 candles for a source flashed area of 100 sq. inches if uncomfortable glare is to be avoided. This is a useful summary, because it applies to the conditions at present most common. A large change in the characteristics of the road surface, however, would render it invalid. It could also be stated, and this replied to Mr. Minchin also, that in the case of most non-cut-off and semi-cut-off installations the first glare source in the field of view caused the greatest discomfort glare (but not necessarily disability glare, Section 9, vb).

It would be difficult to base discomfort effects upon fundamental principles along the lines Mr. Allpress had suggested. As Mr. Waldram had pointed out, discomfort glare depended so much upon psychological conditions that it was probable that each problem had to be investigated separately upon its merits.

For this reason it would be inadvisable to extrapolate the results in order to apply the formula to black-out conditions. Replying to Mr. Beuttell, Mr. Hopkinson said that the formula could be taken to be valid for intensities of fifty candles upwards, and for background brightnesses of 0.005 e.f.c. upwards. No experiments had so far been made below these levels. It was, moreover, most probable, and this was borne out by experiment, that the disabling effects of glare sources were of greater importance under black-out conditions. It was disability glare with which Mr. Allpress had been concerned when he framed his question on the relative visibility with different A.R.P. fittings. Mr. Hopkinson wondered whether Mr. Bennett also had been concerned with the disability glare from low-intensity sources; he had not himself experienced any discomfort glare with the present form of A.R.P. street lighting.

The apparatus and experimental technique used for the investigation could, however, easily be adapted to the obtaining of data on problems of glare under black-out conditions.

Replying to a point raised by Dr. Stiles and elaborated by the President, Mr. Hopkinson drew attention to the check experiments with actual installations which were made from time to time (Section 9, vi.). The results obtained in the laboratory checked closely with conditions of practice, and the opinions had been formed in the installations after driving through them and experiencing the repetitive effect which the President had described.

NOTES ON RECENT MEETINGS AND EVENTS

Informal General Meeting in London.

A very successful informal meeting devoted to "Photometric Reminiscences" was held at St. Ermin's Hotel (Westminster), on February 13. Mr. F. C. Smith (President) presided. Before the meeting commenced a brief interval was afforded for formal business, and the names of new applicants for membership were announced in the usual way.

General regret was expressed that Mr. A. P. Trotter, owing to recent indisposition, had found himself unable to attend the gathering. He had, however, prepared a communication, reviewing developments in illumination photometry from about 1880 onwards, which formed the first item on the programme. Reminiscences were subsequently contributed by Dr. C. C. Paterson, Mr. G. H. Wilson, Mr. E. Stroud, Mr. P. J. Waldram, Mr. F. C. Smith, Dr. J. W. T. Walsh, Mr. A. E. Schuil, Mr. P. Good, Mr. W. J. A. Butterfield, Lt.-Col. Kenelm Edgcumbe, Mr. W. R. Stevens, Mr. J. S. Dow, Mr. C. A. Morton, Mr. A. W. Beuttell, and Mr. K. J. W. Craik.

The meeting, which commenced at 6 p.m., was prolonged until after 9 p.m., when a vote of thanks to contributors terminated the proceedings.

Meetings in Leeds.

The North Midland Centre has now resumed regular meetings.

On January 8 there was an interesting discussion on the lighting requirements in the Factory Act. Mr. F. Baker opened the proceedings by presenting the standpoint of a manufacturer of woollen goods, Mr. A. E. Iliffe reviewed the regulations from the standpoint of the lighting engineer, and Mr. J. Daniel quoted from his experience as a factory inspector in explaining the need for the various conditions prescribed. There was an attendance of forty-five, which included some representatives of the Institution of Production Engineers.

At a subsequent meeting on February 12 Mr. H. Fletcher, who had previously presented a paper before the Society in London, gave an address on "The Maintenance of a Factory Lighting Installation," in the course of which he analysed the costs of maintenance in a factory with which he was familiar and explained the system of cleaning and renewal. The address led to a keen discussion, at the conclusion of which cordial expression was given to the meeting's appreciation of Mr. Fletcher's contribution.

Mr. J. W. Howell, chairman of the North Midland Centre, presided over both gatherings.

Successful meetings have also been held in Nottingham (February 9) and Glasgow (February 16). Reference to these will be made in the next issue of THE TRANSACTIONS.

APPLICATIONS FOR MEMBERSHIP

Elections Pending

The names of the following applicants for membership were presented for the first time at the general meeting on Tuesday, February 13:—

CORPORATE MEMBERS:—

Baker, F.	90, Sandhill Oval, Alwoodley, LEEDS.
Barrett, W. A. G.	15, Netherfield Road, LONDON, S.W.17.
Bayley, F. W.	Siemens Electric Lamps and Supplies, Ltd., 38-39, Upper Thames Street, LONDON, E.C.4.
Debenham, W. F. S.	38, Aylward Road, Merton Park, LONDON, S.W.20.
Kelso, A.	4, Queen's Road, HARROGATE.
Marston, A. H.	216, Oakwood Lane, LEEDS, 8.
Monash, B.	7, Ellesmere Road, Windsor Sl., MELBOURNE, Australia.
Pearce, J. H. G.	Pearce Signs, Ltd., New Cross Road, LONDON, S.E.14.
Rhead, Alan V.	1, Jubilee Terrace, Grandpont, OXFORD.
Sugg, Crawford	Ranelagh Works, Chapter Street, LONDON, S.W.1.
Whitaker, H.	The Rustless Iron Co., Ltd., Trico Works, KEIGHLEY.

COUNTRY MEMBERS:—

KORNHAUSER	Avenue Astrid, Lessines, BELGIUM.
ORDINANZ, W.	6B, Str. Dragos Voda, Iat. Cernauti, ROUMANIA.
WRIGHT, S. L.	Deal and Walmer Gas Company, Cannon Street, DEAL.

Elections Completed

At this meeting the names of those announced on January 9, which were published in the "Transactions" (Vol. IV. No. 12, December, 1939, p. 164), were presented again, and these applicants were formally declared members of the Society.

Nominations for Officers and Council

The attention of members is drawn to the usual list of nominations for officers and council for the coming session (see page 32).

In the present unprecedented circumstances the Council has made a departure by inviting Professor J. T. MacGregor-Morris to assume the Presidency for the coming session. In making this step they were guided by the desire to recognise Professor MacGregor-Morris's long association with the Society and his contributions to the field of photometry. They are also mindful of the fact that Mr. W. J. Jones, the senior Vice-President, has recently assumed new responsibilities which, for the present, may render it difficult for him to give the time to the Society that he would wish, and that it will be to the advantage of the Society, therefore, to defer his term of office until the full benefit of his services in the presidential chair can be obtained.

ELECTION OF OFFICERS AND COUNCIL

SESSION 1940-1941. OFFICIAL NOTICE

IN accordance with the procedure specified in the Articles of the Society, a list of existing Officers and Members of Council, of vacancies occurring and of duly qualified persons nominated by the Council for vacancies about to occur in the offices of President, Vice-Presidents, Hon. Treasurer, Hon. Secretary, and Ordinary Members of Council is presented below for the information of the Members of the Society.

In the event of any Members desiring to put forward other names, the Council will be pleased to receive such nominations, which should be made in accordance with the following rule (Article 48):—

> "After the issue of the Council's list, and not later than the 15*th day of April* next following, any ten Members (but no more than ten) may nominate any other duly qualified person to fill any such vacancy by delivering such nominations in writing to the Hon. Secretary, together with the written consent of such person to accept office if elected, but each such nominator shall be debarred from nominating any other person for the same office at such election."

Present Officers and Members of Council

President*:—*Mr. F. C. Smith, M.Inst.Gas E.

***Past Presidents*:—**

Mr. A. P. TROTTER, M.INST.C.E.
Sir JOHN HERBERT PARSONS, C.B.E., F.R.S.
Sir DUNCAN WILSON, C.V.O., C.B.E.
Dr. C. C. PATERSON, O.B.E., M.INST.C.E., M.I.E.E.
Dr. J. W. T. WALSH, M.A., M.I.E.E.
Lt.-Col. K. EDGCUMBE, T.D., M.INST.C.E., M.I.E.E.
Lt.-Com. HAYDN T. HARRISON, M.I.E.E., R.N.V.R.
Mr. C. W. SULLY.
Mr. H. HEPWORTH THOMPSON.
Mr. A. W. BEUTTELL, M.I.E.E.
Mr. A. CUNNINGTON, B.SC., M.I.E.E.
Dr. S. ENGLISH, F.I.C., F.INST.P.
Mr. PERCY GOOD, M.I.E.E., F.I.C.G.

***Vice-Presidents*:—**

Mr. W. J. Jones (1937)
Col. C. H. Silvester Evans (1938)*
Mr. R. O. ACKERLEY (1939)

***Members of Council*:—**

Mr. T. C. ANGUS (1938)
Mr. B. F. W. Besemer (1937)
Mr. H. Bright (1937)
Dr. H. Buckley (1938)
Mr. T. CATTEN (1939)
Mr. DEAN CHANDLER (1939)
Mr. W. N. C. CLINCH (1938)
Mr. J. F. Colquhoun (1937)
Mr. L. J. DAVIES (1938)
Mr. W. J. EDWARDS (1939)
Mr. C. E. GREENSLADE (1939)
Mr. A. V. HORSFALL (1938)
Mr. F. E. Lamplough (1939)*
Mr. H. LINGARD (1939)
Mr. J. S. Preston (1937)
Mr. T. E. RITCHIE (1939)
Mr. K. F. SAWYER (1939)
Major P. A. SMITH (1938)
Mr. E. J. Stewart (1939)
Mr. L. M. Tye (1937)
Mr. G. H. Wilson (1937)

Hon. Secretary*:—*Mr. J. Stewart Dow (1928)

Hon. Treasurer*:—*Mr. E. W. Murray (1939)

Nominated by the Council to fill Vacancies

***President*:**—Professor J. T. MACGREGOR-MORRIS, M.I.E.E.

***Vice-Presidents*:—**

Dr. H. BUCKLEY, F.INST.P.
Mr. E. J. STEWART, M.A., B.SC.

***Members of Council*:—**

Mr. R. W. DANIEL
Mr. G. DIXON
Mr. N. V. EVERTON
Mr. G. W. GOLDS
Mr. H. LONG
Mr. R. MAXTED
Mr. G. W. M. PHILLIPS
Mr. E. STROUD
Mr. J. M. WALDRAM

***Hon. Secretary*:**—Mr. J. S. DOW

***Hon. Treasurer*:**—Mr. E. W. MURRAY

The names in italics are those of retiring Officers or Members. The date in parentheses after each name indicates the date of election to Office or Membership of the Council. In addition to the above the Chairmen of the various Local Centres are Members of Council during their period of Office. *Indicates resignation.

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FUNDAMENTAL PRINCIPLES OF METERS USED TO MEASURE VISIBILITY

By C. DUNBAR, M.Sc. *(Member).*

(Paper read before the Photometry Section on April 4th, 1939).

SUMMARY.

Attention is drawn to the difficulty of assessing the visibility of an object when the difference in brightness between the object and its background exceeds the value necessary to produce the best performance under the particular experimental conditions. It is suggested that if the visibility scale is to be extended to brightness differences which exceed this value, then the visibility of the object must be considered in terms of the observer's performance under all conditions of sensitivity, distraction, attention, and unexpectedness which can occur in practice during the carrying out of the visual task.

Meters which have been designed to measure the visibility of an object depend upon making the visual conditions more difficult by producing optically a condition in which the difference in brightness between the object and its background is equal to a threshold value. It is shown that in the case of objects which are presented against backgrounds of different brightness, these objects will be arranged in an order of visibility which depends on the exact manner by which the threshold condition is produced. Inconsistencies which may arise from the use of a meter both in the presence and absence of glare sources are also indicated. The need is stressed for careful consideration of the results given by a meter both in relation to the nature of the visual task and the differences in lighting conditions under which comparisons of visibility are made.

Consideration is also given to visibility meters which have been designed to measure the efficiency of street lighting installations. As these meters take into account many of the factors affecting the visibility of objects in the street, they can usefully be employed to study the effect of these factors. On the other hand, since the meters do not take all the important factors into account, the results given by the meters in different installations should not be taken as measuring the efficiency of these installations in promoting object visibility.

1. General Consideration of the Problem of Visibility.

Introduction.

The term "visibility" has been used in so many different senses that it is essential that any treatment of a visibility problem should be accompanied by a statement of what the writer means by this term. This paper is concerned with the visibility of objects, and the visibility of an object may be defined as the ease with which the object can be seen under the conditions prevailing when the object is presented to the observer.

In the sense in which it is defined above, the visibility of an object is a very complex conception, but in most lighting problems it is of great importance to know the various factors which together determine it. The fundamental work ([1, 2, 3, 4]) on this subject has been carried out in the laboratory under relatively simple but carefully standardised conditions, and has generally been directed towards the determination of the brightness difference threshold, i.e., the difference in brightness between an object and its background which, under a specified set of experimental conditions, will give an observer an equal chance of detecting or missing the object. The various factors which influence visibility have been studied in relation to the changes which they produce in the brightness difference threshold.

It has been shown in this way that the visibility of an object depends on the size, brightness, and colour of the object and on the brightness and colour not only of that region of the background against which the object is presented to the observer but also of all other regions of the observer's field of view.

A complete specification of the physical characteristics of the observer's visual field does not, however, define the visibility of the object, for it is clear that visibility must depend not only on the nature of the light stimulus received by the eye but also on the interpretation which the observer places on the visual impression produced by this stimulus. This interpretation will vary from observer to observer, and will also vary from time to time with the same observer on account of factors such as attention, distraction, and unexpectedness. Thus the visibility of an object can strictly have no meaning except in relation to an observer who is viewing the object at a particular time. When considering visibility in relation to any practical visual task it will generally be necessary to introduce a rather broader conception of visibility than that out-

lined above. Further consideration is given to this point later.

VISIBILITY SCALE.

Let T_B be the threshold difference in brightness for an object of a particular angular size which is presented against an extended background of brightness B. Then it has been shown that the ratio T_B/B is related to B by a curve of the type shown in Fig. 1 (5). Over a certain range of background brightness T_B/B is approximately constant (Fechner's law).

Since, by definition, objects which present their threshold differences in brightness have the same probability of detection, it seems reasonable to say that they have the same visibility. The curve in Fig. 1 may, therefore, be taken as defining conditions under which the object will have a constant visibility.

VARIATION OF $\frac{T_B}{B}$ WITH B.

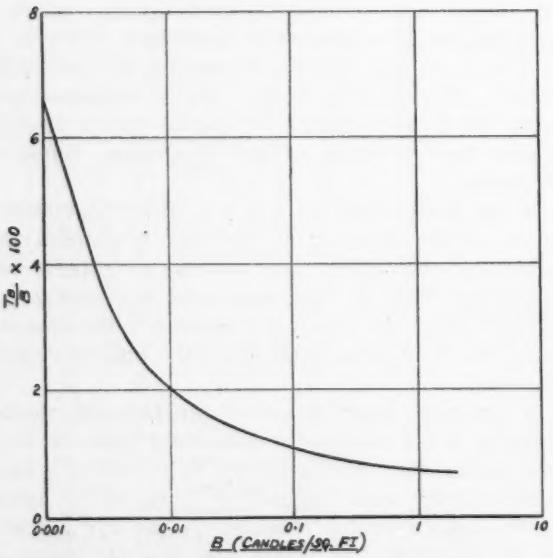

Fig. 1.

So far we have considered only that point on the visibility scale at which the object has a 50 per cent. chance of detection. If the brightness of the background is kept constant and the brightness b of the object is changed, it has been shown that the probability of detection, P, of the object varies with the ratio $\left(\frac{B-b}{T_B}\right)$ in a manner similar to that shown in Fig. 2 (6). $P = 0.5$ when $(B - b) = T_B$. A probability curve of this type constitutes a visibility scale for the object when the background brightness is constant.

PROBABILITY CURVE.

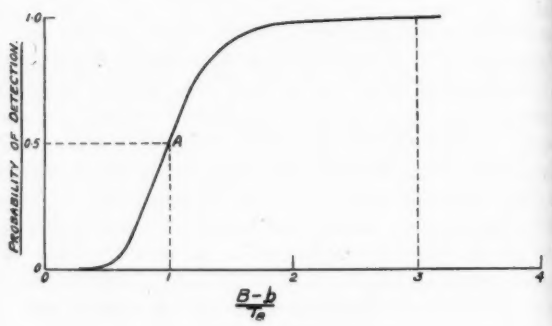

Fig. 2.

The probability curves obtained for the object at different background brightnesses must all pass through the point A in Fig. 2. The question immediately arises as to whether the curves have the same or different gradients, i.e., whether the same value of $\left(\frac{B-b}{T_B}\right)$ will, at different background brightnesses, always give the object the same visibility or not. The importance of the answer to this question will be apparent when the results given by different visibility meters are discussed later. It should be noted that if the probability curves have the same gradient, then any curve which is obtained simply by multiplying every ordinate of the curve in Fig. 1 by a constant factor will be an equal visibility curve for the object.

Returning to the curve in Fig. 2 it will be seen that the object is certain to be detected when the difference in brightness between the object and its background is roughly equal to three times the threshold difference in brightness, but in any practical problem we must be prepared to differentiate between the visibilities of objects all of which can be seen with certainty under the prevailing experimental conditions. For example, the driver of a car may be able to regard two objects as both fully visible in the sense of the laboratory experiment and yet judge that one object will be less easily seen than the other among the distractions which may occur on the road. In considering visibility in relation to any practical visual task we must extend our ideas beyond the laboratory case of an observer in a certain standardised condition and consider visibility

in relation to the average probability of detection of the object when account is taken of all conditions of sensitivity, attention, distraction, and unexpectedness which can occur in practice during the performance of the visual task.

This extension of the idea of visibility will mean that if T_B is now the threshold difference in brightness for some particular and standard observer condition, the curve relating the average probability of detection of the object to the ratio $\left(\frac{B-b}{T_B}\right)$ will have a much smaller gradient than the curve shown in Fig. 2. In considering the results given by visibility meters which have been designed to measure visibility in this widened sense we shall still, however, be primarily interested in the question as to whether, at different background brightnesses, the same value of $\left(\frac{B-b}{T_B}\right)$ will give the object the same visibility or not.

2. Visibility Meters.

Principles of Visibility Meters.

The general principle of all visibility meters is to bring about a condition in which the difference in brightness between the object and its background has a threshold value. This can be done in a number of ways, and those utilised in existing meters are classified below:

(a) The brightness of both object and background can be reduced in the same ratio by means of a simple absorbing wedge.

(b) The contrast between the object and its background can be reduced without any appreciable change in the general brightness of the field of view by means of a wedge or number of similar plates, which partially diffuse, but do not absorb, light. ([7])

(c) The contrast between the object and its background can be decreased and the general brightness of the field of view also decreased by means of a wedge or series of plates which both absorb and diffuse light. A photographic wedge, for example, behaves in this way. ([8, 9])

(d) The contrast between the object and its background can be decreased by superimposing on them the image of an illuminated surface. In an existing instrument this method is combined with a reduction of the brightness of both object and background by means of an absorbing wedge. ([10])

In the case of meters which fall in the classes (a) to (c), the visibility of an object can be arbitrarily expressed in terms of the wedge density, or number of similar plates, necessary to produce a threshold condition. Luckiesh and Moss([8]), however, who have designed a meter utilising a photographic wedge, calibrate their meter against a visibility scale set up by a number of white test cards, each of which has a black spot at its centre. The various spots subtend angles at the observer's eyes varying from 1′ to 20′. All the cards have an illumination of 10 ft.c. The point on the wedge through which the 1′ spot is just invisible is given a scale reading of unity, and so on, to a scale reading of 20. The type of test pattern is changed if the instrument is to be used for a visual task which involves more than the mere recognition of the presence of an object.

3. Results Given by Visibility Meters.

Conditions for Equal Visibility.

A visibility meter which falls in one of the classes (a) to (c) automatically gives the same visibility to objects which are just invisible through the same region of the wedge employed, or through the same number of similar diffusing plates. The implications of this fact are examined in detail below. For the sake of conciseness, a variable number of plates will be taken to constitute a wedge.

Consider an object of brightness b, which is seen against an extended background of brightness B. The observer looks through the meter at the object and alters the wedge until the object is just invisible. Suppose that the region of the wedge through which the object is just invisible has a direct transmission factor τ, i.e., a fraction τ of the light incident on the wedge is transmitted unscattered. Suppose also that as the result of diffusion in the wedge a brightness k is superimposed on both object and background per unit brightness of the external field. Then, if b′ and B′ are the brightnesses of the object and background as seen through the wedge,

$$B' = \tau B + kB \quad \ldots\ldots\ldots\ldots (1)$$

$$\text{and } b' = \tau b + kB \quad \ldots\ldots\ldots\ldots (2)$$

It is assumed here that the object is small in comparison with the background, so that the object brightness makes a negligible contribution to the diffuse brightness produced by the wedge. Subtracting equations (1) and (2), we have

$$B' - b' = \tau(B - b) \quad \ldots\ldots\ldots\ldots (3)$$

and dividing each side of equation (3) by B′,

$$\frac{B'-b'}{B'} = \frac{\tau}{\tau+k} \cdot \frac{B-b}{B} \quad \ldots\ldots\ldots\ldots (4).$$

As the object is just invisible when viewed through the wedge, (B′ − b′) is the threshold difference in brightness at a background brightness B′, and $\frac{B' - b'}{B'}$ is the value of the Fechner fraction at this background brightness.

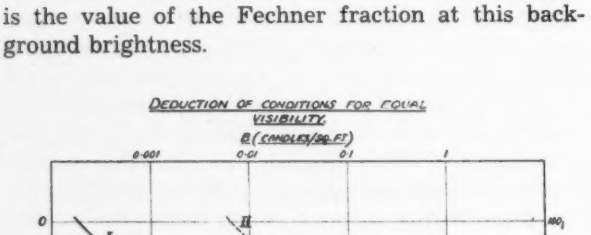

Fig. 3.

Curve I. in Fig. 3 is a curve which relates the logarithm of the Fechner fraction to the logarithm of the background brightness for an object which subtends an angle of 1½° at the observer's eye. The curve was obtained in the laboratory by the writer, the object being seen against a background which was uniform in brightness. With the aid of this curve and equations (1) and (4) we can see the way in which a meter operates.

Suppose that the value of $\log\left(\frac{B-b}{B}\right)$ for an object of this angular size is represented by the point A in Fig 3. The action of a wedge in making this object just invisible is to displace A to some point C on the Fechner fraction curve. It follows from equations (1) and (4) that

$$DA = -\log\left(\frac{\tau}{\tau+k}\right)$$

$$\text{and } CD = -\log\ (\tau+k)$$

For the particular wedge setting which makes this object just invisible, τ and k are constants, and hence $\left(\frac{\tau}{\tau+k}\right)$ and $(\tau+k)$ are also constants. It follows that if we consider a large number of objects of this angular size, but which are seen against backgrounds of different brightness, and all the objects are made just invisible by the same wedge setting which makes the object represented by the point A just invisible, then the values of $\log\left(\frac{B-b}{B}\right)$ for these objects must lie on a curve which is obtained by displacing the Fechner fraction curve in Fig. 3 bodily, but without rotation, until C falls on A. This gives Curve II. in Fig 3.

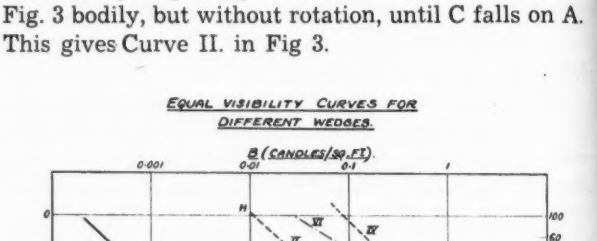

Fig. 4.

It is obvious that the way in which the point A is displaced on to the Fechner fraction curve depends entirely on the optical properties of the wedge used. Referring to Fig. 4, a simple absorbing wedge (i.e., k=0) will displace A along a horizontal line to C′. In the case of a wedge which partially diffuses but does not absorb light, if the apparent brightness of the background as seen through the wedge was equal to the actual background brightness, A would simply be displaced vertically on to the Fechner fraction curve. Since, however, a diffusing wedge must necessarily cause a reduction in apparent brightness of the background, there is also a horizontal displacement represented by DC, where CD $\triangleq -\log 0.5 = 0.3$*. A wedge which partially absorbs and partially diffuses light will displace A to some point on the Fechner fraction curve lying between C and C′. Thus a simple absorbing wedge would give the same visibility to objects for which the values of $\log\left(\frac{B-b}{B}\right)$ lie on Curve II. in Fig. 4. Curve III. is the corresponding curve for a diffusing wedge with no absorption. A wedge which both absorbs and diffuses will give a curve lying between Curve II. and Curve III.

* The value of k for any region of a diffusing wedge will depend to some extent on the angular size of the background. Measurements of the transmission and scattering coefficients of a number of etched glasses have shown that, if the background subtends an angle of 20° at the eye, a glass for which $(\tau + k) = 0.5$ will obscure greater contrasts than those in which we are interested here. For simplicity it will be assumed that for every region of a wedge of this type $(\tau + k) = 0.5$. As the true value of $(\tau + k)$ for any particular object contrast and for this size of field will lie between 0.5 and 1.0 the above assumption will have little effect on the form of the curve obtained on translation.

Consider any point H on Curve II., and let the ordinate to this point cut the Fechner fraction curve at G. Then the ratio of the values of $\left(\frac{B-b}{B}\right)$ at the points H and G gives the multiple of its threshold difference in brightness (i.e., the value of $\left(\frac{B-b}{T_B}\right)$) which an object seen against a background brightness B must present in order that a simple absorbing wedge should assess the object as being equally visible with object A. In a similar manner, the values of $\frac{B-b}{T_B}$ for equal visibility demanded by a diffusing wedge can be obtained from Curve III.

In Fig. 4, the object A has been arbitrarily selected as presenting 3 times its threshold difference in brightness at a background brightness of 1 candle/sq. ft. The values of $\frac{B-b}{T_B}$ which are required by the two types of wedges in order that objects seen against other background brightnesses should have the same visibility as object A are given in Table I. Values of $\frac{B-b}{T_B}$ are also given for the case in which the object A presents 10 times its threshold difference in brightness. The translation curves for this case are Curves IV. and V. in Fig. 4, the latter curve corresponding to the diffusing wedge.

TABLE I.

Value of $\frac{B-b}{T_B}$ for object A	Background brightness (c./sq. ft.)	$\frac{B-b}{T_B}$		
		Diffusing Wedge	Absorbing Wedge	Luckiesh-Moss Meter
3	10	2.8	1.6	—
	1	3.0	3.0	
	0.1	3.4	7.8	
	0.01	4.1	21	
10	10	9.6	3.0	3.5
	1	10	10	10
	0.1	12	44	23

If we consider an object which is seen against a background of a particular brightness, any meter, irrespective of the type of wedge which it employs, will give the object a higher visibility the greater the difference in brightness between the object and its background. In this restricted case of a background of fixed brightness, all meters will arrange objects of the same size in the same order of visibility.

On the other hand, if the meters are used to compare the visibilities of objects which are seen against backgrounds of different brightness, meters employing different types of wedges will give totally inconsistent results. For example, referring to Table I., a simple absorbing wedge would give the same visibility to objects which present respectively 21 and 3 times their threshold difference in brightness at background brightnesses of 0.01 and 1 candle/sq. ft. A wedge which partially diffuses light but does not absorb would require these multiples to be 4.1 and 3. It should be noted that each type of wedge would agree that two objects which presented 21 and 4.1 times the threshold difference in brightness at a background brightness of 0.01 candle/sq. ft. had very different visibilities.

A wedge which both absorbs and diffuses will give values of $\frac{B-b}{T_B}$ intermediate between those listed in Column 3 and Column 4 in Table I. For example, experiments carried out with a Luckiesh-Moss meter and using a fixed scale reading of 5, gave Curve VI. in Fig. 4 as an equal visibility curve, and the corresponding values of $\frac{B-b}{T_B}$ are given in Table I.

The results obtained in this analysis may be briefly summarised as follows:—

(a) A wedge which partially diffuses light but does not absorb will give the same visibility to objects which, at different background brightnesses, present approximately the same multiple of their threshold differences in brightness.

(b) A simple absorbing wedge requires for equal visibility a rapidly increasing multiple of the threshold difference in brightness as the background brightness decreases.

(c) The discrepancy between the results given by the above types of wedge increases as the contrast increases.

It should also be noted that, since at higher brightnesses than 1 candle/sq. ft. the Fechner fraction is practically a constant, a greater discrepancy between the results given by different wedges would have been obtained if the object A had been assumed to be presented against a higher background brightness than 1 candle/sq. ft.

As the above analysis is independent of any visibility scale against which a meter may be calibrated, and considers only the question of objects which are given the same visibility, it is evident that if a meter is to be used to compare the visibility of objects seen against backgrounds of different brightness, the

results given by the meter will require justification. Only one type of wedge can arrange objects in their correct order of visibility for the particular visual task involved.

So far we have considered only those meters which produce a threshold condition by means of an optical wedge. Mention has been made, however, of another type of meter ([10]) in which the threshold condition is produced by superimposing the image of an illuminated surface over the observer's field of view. At the same time, the brightness of both object and background are reduced by means of an absorbing wedge. The brightness of the illuminated surface and the density of the wedge are increased in such a way that the apparent brightness of the background against which the object is presented remains approximately constant. If B_c is the value of the veiling brightness and T_a is the transmission of the wedge when the object is just invisible, the visibility of the object is taken as proportional to $\frac{B_c}{T_a \cdot B}$, where B is the brightness of the background against which the object is presented. The instrument is intended for use in circumstances in which the background brightness falls in the range in which the Fechner fraction is constant. It follows, therefore, that this meter will give the same visibility to objects of the same size when the values of $\frac{B-b}{T_B}$ for these objects are equal.

Effect of Glare

We have considered only the results given by meters for the case where objects are seen against extended backgrounds which are uniform in brightness. Visibility meters may be used, however, to compare the visibility of objects under different conditions of glare. ([11])

It is well known that the effect of a glare source on the visibility of an object is the same as if a veiling brightness was superimposed over both object and background, the value of this veiling brightness being equal to $\frac{kE}{\theta^n}$, where k and n are constants. ([2, 3]) E is the illumination produced in the plane of the observer's eye by the glare source and θ is its angular separation from the observer's direction of view. If the angle θ is increased but at the same time the candle-power of the glare source is increased so that $\frac{E}{\theta^n}$ remains constant, then the visibility of the object will also remain constant.

This result may be compared with that which will be given by a visibility meter whose wedge causes a certain degree of diffusion. The light incident on the wedge from the glare source will produce a diffuse brightness which will depend mainly on the candle-power and distance of the glare source and which, especially for small values of θ, will be practically independent of θ. It is to be expected, therefore, that if E and θ vary in such a way that E/θ^n remains constant, the wedge will demand a rapidly increasing difference in brightness between the object and its background as θ increases in order that the object shall keep the same visibility.

This fact has been confirmed by tests which have been carried out with a Luckiesh-Moss visibility meter. An observer viewed a test spot which subtended $1\frac{1}{2}°$ at his eyes against a background whose brightness was 0.8 candle/sq. ft. A glare source was displaced from the observer's direction of vision by an angle of 3°, and the intensity of the glare source was such that the observer's threshold difference in brightness in the presence of the glare was 60 per cent. higher than in the absence of glare. The observer looked at the test spot through a Luckiesh-Moss meter which was set at a scale reading of 5. The observer adjusted the spot brightness until the spot was just invisible through the wedge. The glare source was then displaced to another and larger angle θ, and the intensity increased until the observer's threshold assumed the same value as it had for the previous position of the glare source. It could then be inferred that E/θ^n had the same value as previously. The spot brightness was again adjusted until the spot was just invisible through the meter at a scale reading of 5. In this way it was found that as the angle θ increased from 3° to 12°, the difference in brightness between the object and its background had to be increased six times in order that the object should be given the same visibility by this wedge.

It is interesting to note in this connection that the Luckiesh-Moss meter has recently been modified by fitting it with an extension tube which screens the glare source from the eyes of the observer. ([12]) The end of the tube remote from the meter is covered with a diffusing medium, which produces a diffuse brightness due to the glare source which is proportional to E/θ^n. This diffuse brightness is, of course, superimposed on the visual field of the observer. It should be emphasised that without some device such as this a meter whose wedge causes diffusion must not

be used to make comparable measurements of visibility with and without glare.

In the case of a meter whose wedge is of the simple absorbing type, all brightnesses in the visual field (including that of the glare source) are reduced in the same ratio by the wedge. The effect of the glare source on the visibility of the object does not remain the same, however, as the general brightness of the field is reduced.

4. Justification of a Meter.

It was pointed out in Section 1 that in considering visibility in terms of the average probability of detection of the object under all conditions of the observer which could occur in practice, we should be primarily interested in the question as to whether the same value of $\left(\frac{B-b}{T_B}\right)$ would, at different background brightness, give an object the same visibility or not. It has been shown in Section 3 that while one type of meter demands for equal visibility almost a constant value of $\left(\frac{B-b}{T_B}\right)$, another demands that this ratio should increase rapidly as the background brightness decreases.

It is apparent that if a meter is to be used to measure visibility at different background brightnesses in relation to some particular visual task, it is not sufficient merely to select a convenient form of meter and to calibrate it against a particular visibility scale. It is necessary, in addition, to have some experimental justification for the results given by the meter.

The obvious method of obtaining such evidence would be to carry out a statistical survey over a period of time of the number of occasions on which objects under different lighting conditions were detected or recognised, according to the requirements of the visual task. This method would necessarily be long and tedious. An alternative method would be to accumulate a mass opinion as to the relative visibilities of objects under different lighting conditions.

An example of the latter method of approach to the visibility problem is afforded by an experiment [13] carried out by the writer in which car-drivers were asked to assess the difference in brightness between an object and its background which, at different background brightnesses, was just sufficient for safe driving at 30 m.p.h. The results of this work indicated that objects in the street would have the same visibility when the ratio of $\left(\frac{B-b}{T_B}\right)$ for the objects was approximately constant, T_B being the threshold difference in brightness determined in the laboratory for a background of brightness B. A meter which is to be used to assess the visibility of objects in street-lighting installations should give results which are consistent with this work.

The general conclusion which must be drawn from what has been set out in the foregoing sections of this paper is that the results given by a meter must be treated with great caution until these results have been carefully considered both in relation to the exact nature of the visual task and the differences in lighting conditions under which comparisons of visibility are made.

5. Meters Designed for Measuring Efficiency of Street Lighting Installations.

This paper has so far been devoted exclusively to the consideration of meters which are used to assess the visibility of objects under different lighting conditions. It should be noted, however, that there are other types of "visibility" meters [14, 15] which have been designed to measure the "efficiency" of highway lighting. These meters are really threshold meters which give either the difference in brightness T between an object and its background which is necessary in order that an object should just be perceived against a particular region of the background in a street lighting installation, or the ratio of T to the background brightness B.

Holst and Bouma [14], for example, have designed an instrument which consists essentially of a telescope through which the observer looks at the installation. In the focal plane of the eye-piece is a glass disc on which is a number of small spots of varying transmission. By rotating the disc any one of these spots can be presented against a selected region of the background. If the spot which is just visible has a transmission τ, then the value of $\frac{T}{B}$ for this region is $(1 - \tau)$.

Since these threshold values are determined with the eyes of the observer subjected to the glare from the street lamps, it is obvious that a meter of this type could usefully be employed to consider the effect of glare on the brightness difference necessary to reveal an object to road users. At least one instrument has been specially designed for this pur-

pose, although in this case it has been called a glare meter. (16)

Great care must be exercised, however, in comparing the values of $\frac{T}{B}$ obtained in different installations. There is a tendency to consider that if the values of $\frac{T}{B}$ obtained in one installation are higher than in another, the visibility of objects in the first installation will be lower than in the second.

Such a conclusion is, however, not necessarily correct. The practical objects which at different times are presented to road users against any region of the background in a street lighting installation have a large range of brightness depending on the distribution of illumination on vertical surfaces and on the range of reflection factor which practical objects can have. If a region of the background has a brightness B, and the threshold difference in brightness determined for this region is T, then objects which have brightnesses lying between (B + T) and (B − T) will not be revealed against the region when the objects are presented under conditions similar to those under which the threshold value was determined. Any factor which increases the value of $\frac{T}{B}$ for this region will tend to decrease the percentage number of practical objects which are seen against this region, and also to decrease the visibility of those objects which are still revealed.

If we consider a number of regions of the same brightness in different installations, the values of $\frac{T}{B}$ for these regions will vary, depending on such factors as glare, colour and brightness diversity. In each case, the value of $\frac{T}{B}$ will be a measure of that range of object brightness which will not be revealed against the region concerned. No conclusions can be drawn, however, as to the percentage number of practical objects which will not be revealed against each region, or the relative visibilities of those objects which are revealed. The efficiency with which any region A reveals practical objects depends on the number of objects which can have brightnesses which lie in the range $(B_A + T_A)$ to $(B_A - T_A)$, and hence on the distribution of vertical illumination in the installation in which the region A occurs. It is evident that without taking this factor into account it is not possible to form an opinion as to the relative efficiencies of regions in different installations. A detailed consideration of the revealing power of street-lighting installations will be found in three papers published previously in these "Transactions." (17, 13, 18)

ACKNOWLEDGMENT.

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DISCUSSION

Colonel C. H. SILVESTER EVANS, in opening the discussion, said that all present would appreciate Mr. Dunbar's critical analysis of visibility meters, but he noticed that Mr. Dunbar had rather avoided saying whether he considered any visibility meter was good for any purpose! He was not prepared to say that a visibility meter was of no use—but it was imperative that one should define clearly the purpose for which it was required. It would be impossible to produce a meter which would serve all purposes, because, for example, the visibility requirements of an airman, a sailor, and a motorist were entirely different. It might also be pointed out that the rather empirical estimations of visibility as made by the Meteorological Office no doubt served admirably the purpose for which they were intended, though they could have little application for many problems connected with visibility.

One special problem in which he (Colonel Evans) was interested was the visibility of an object in the beam of a searchlight—it might be a ship on the water or an aeroplane in the sky. He had found

that the neutral wedge type of instrument was quite unsuitable, and gave a big spread of results, whereas instruments incorporating a number of diffusing screens answered very well. He emphasised, however, that it was only in connection with this type of measurement that this form of instrument had been found so satisfactory.

The instrument that he was using gave very good reproducible results, and he knew that for the same conditions in any part of the world the meter would give the same reading. On the other hand, if it were applied for some quite different purpose, for example, to determine the visibility of railway signals by night, it might produce very misleading results. Any visibility meter should be calibrated under conditions approaching as nearly as possible to those under which it was intended to be used.

Dr. J. W. T. WALSH agreed with Colonel Evans that it was impossible to take the results obtained by measurements on one particular type of task and apply them to other tasks of entirely different characters. This point had arisen in connection with the problem of assessing how much illumination each operator required in order to carry out typical tasks in factories. It had been suggested that a schedule of values of illumination could be prepared, based on the assumption that the illumination would be adequate if the operator could still just carry on his job if the general brightness were reduced by interposing a screen of, say, 5 or 10 per cent. transmission. His own impression was that such a method would not answer; for, as Mr. Dunbar had shown, if one obtained a certain result on one particular task and tried to relate it to another, one might be completely led astray. In this connection Dr. Walsh referred to work done by Mr. H. C. Weston in this field, and asked whether Mr. Dunbar had compared his results with those obtained by the aid of visibility meters.

Dr. W. S. STILES emphasised the important difference between the smallest difference of brightness perceptible under test conditions and the smallest difference of brightness giving satisfactory visibility of an object under practical conditions in every-day life. As a rule the effective threshold value under practical conditions was a considerable multiple of the threshold value under test conditions. We might believe that this difference would disappear if we could reproduce in our test all the factors which operate in practice. It was not enough, however, to reproduce the correct lighting distribution, the correct size of object, etc. We had also to take account of such factors as the distribution of attention, foreknowledge of the object to be seen, the "meaning" of the object, psychological attitude of the observer, and so on.

When we were presented with two objects or a single object under different lighting conditions we were frequently prepared to assert that the visibility of the object was greater in one case than in the other, although we could, in fact, see the object in both cases. Presumably, in making such a judgment, we imagined the conditions of observation to become more difficult. For example, we might imagine that we gave the object only a fleeting glance or that our attention was mainly directed to another object, and we estimated, mentally, that under the more difficult conditions we should lose sight of the object in one case but not in the other. In some such way as this we could place objects in a certain "order of visibility."

By means of visibility meters of the type of the Luckiesh-Moss meter the conditions of observation were made more difficult in a particular way, namely, by reducing the brightness of the field of view (absorbing action) and at the same time reducing the relative differences of brightness of different parts of the field (diffusing action). A visibility meter of given absorbing and diffusing properties used by a given observer would yield a particular "order of visibility." It could be shown by the methods used by Mr. Dunbar that the order of visibility given by different meters of the type in question depended on the relative absorbing and diffusing properties of the wedge. Thus we had various orders of visibility from which to choose: those derived from the mental estimates of observers, those obtained with various absorbing-diffusing wedges, and those which would be yielded by other types of visibility meter which could be devised. The only justification for accepting any of these orders of visibility would be that under actual conditions we should, in fact, see an object higher in the scale more frequently than any object lower in the scale. Despite the large amount which had been written about visibility meters of the type mentioned little, if any, evidence had been put forward to show that the order of visibility could be justified in the way just explained.

Mr. J. S. Dow agreed with previous speakers in regard to the difficulty of applying results obtained with a certain instrument for a certain process to other quite different operations. Nevertheless, he would

like to hear whether the author thought it possible to affirm the principle that if operations commonly performed in offices and factories could just be carried on when the general brightness level was reduced, say to 1/50th of that existing, then the existing brightness, and therefore the illumination provided, could certainly be considered adequate. It was not a scientifically accurate method that was aimed at, as admittedly the effect of increasing brightness or contrast must be different with different operations, but only a rough empirical guide that might be adopted in practice.

Mr. Dow also remarked that the fundamental weakness of all existing methods of measuring visibility seemed to be that they all depended on a threshold process—one ascertained how greatly the existing facilities had to be weakened before one could just *not* do a thing. This was quite different from the estimate one really sought—a means of judging the degree of ease with which operations were carried out under the existing conditions. In conclusion, Mr. Dow asked Mr. Dunbar to explain more fully in what circumstances a combination of diminution in brightness with an increase in veiling or diffusing effect was desirable in a visibility meter.

Mr. J. M. WALDRAM said that Mr. Dunbar's analysis of visibility meters had been very thorough and had been very fair in his criticisms. The limitations and imperfections of such instruments would be admitted, but those associated with their design had done a great deal to stimulate interest in " the science of seeing " and to establish the factors on which visibility depended. Previous speakers had placed emphasis, very properly, on the fact that one could not design an omnibus instrument capable of performing many different tasks whilst still remaining simple to operate. It was, however, equally important to have a clear conception of what one did want to measure, and then to aim at doing that one thing well.

Mr. C. DUNBAR, in his reply, said that he was glad that all the speakers had appreciated the fact that it was impossible to design a visibility meter which would correctly assess visibility in relation to every kind of visual task. He had shown in the paper that a meter would arrange objects in an order of visibility which depended on the manner by which the threshold condition was produced. There were many methods of producing a threshold condition, not all of which had as yet been incorporated in visibility meters. As Dr. Stiles had rightly emphasised, we could only accept one of the many possible orders of visibility given by different meters for the same visual task if it was shown that this order was in agreement with the probability of detection of the objects—or in the case of a bench task, with the efficiency with which the task could be performed—under practical conditions.

Colonel Evans had made an important point when he said that an investigator should define clearly what a meter was intended to measure. A great deal of confusion and criticism had been caused through the use of the term " visibility " with different shades of meaning. Mr. Dunbar was interested in the fact that Colonel Evans had had a similar experience to himself in using meters which caused a large reduction in brightness of the visual field. It was possible that inconsistencies arose from the fact that an observer tended to increase the density of the wedge too rapidly, so that the adaptation of the eye could not follow sufficiently quickly the change in brightness of the visual field. In considering the results given by such meters, he had found it most convenient to use a fixed wedge reading and, after allowing time for the eye to become adapted, to adjust the object brightness until the object was just invisible. In this way it was possible to obtain quickly a large number of observations of the object brightness which this region of the wedge would render just invisible without upsetting the adaptation level. Such a device could not be used, however, in a practical application of the meter. It was true that a meter employing diffusing screens which did not seriously reduce the field brightness would be free from such troubles, but it must not be assumed that if a meter gave a consistent answer under the same set of lighting conditions, the answer was necessarily correct.

Both Dr. Walsh and Mr. Dow had raised the question as to whether the illumination on every bench or office task could be considered adequate if in each case the operator could just carry on his job when the illumination was reduced to some particular and constant fraction of its original value. Mr. Dunbar agreed with Dr. Walsh that it would be unsound to specify illuminations in this way, since the types of visual task included in the above categories would vary enormously. When considering the question of adequate illumination the first impulse would be to think of this illumination in terms of production. It was very probable that a greater multiple of the threshold illumination would be necessary in order to obtain the maximum of production in the case of tasks in which vision was

the predominating factor than in others in which vision was simply a guide to labour. Mr. Dunbar pointed out, however, that Dr. Luckiesh had frequently stressed the fact that production was not a complete guide to ease of seeing. The ultimate effect of the task on the individual had also to be taken into account. In work such as that carried out by Mr. Weston it was found that a large increase in illumination above a certain value gave a negligibly small increase in performance. It would be unwise, however, to assume that the lower illumination was adequate for the task, since the further large increase in illumination might have a tremendous effect in protecting the eyes and improving the general health of the individual. Until this question had been studied in relation to different types of visual tasks, Mr. Dunbar thought it would be premature to lay down any particular multiple of the threshold illumination as being adequate. With regard to the second part of Dr. Walsh's contribution, Mr. Dunbar regretted that as yet he had not had an opportunity of comparing the results given by visibility meters with those obtained by Mr. Weston.

Mr. Dow had also asked as to the circumstances in which a meter should employ a wedge with both absorbing and diffusing properties. It seemed to Mr. Dunbar that if one wished to design a meter for any particular visual task it was necessary first of all to obtain either statistical evidence as to the probability of detection of objects under different lighting conditions, or to obtain the mass opinion of observers as to the relative visibilities of the objects, and then to design a meter which would arrange the objects in the correct order of visibility. So little work had been carried out above threshold conditions that it did not seem possible to give a satisfactory answer to Mr. Dow's question. This might seem illogical in view of the existence of visibility meters, but, as Dr. Stiles had pointed out, little attempt had been made to justify the results given by the meters.

Mr. Dunbar said he greatly appreciated Dr. Stiles's comments on the visibility problem, and was entirely in agreement with him. He also agreed with Mr. Waldram that, in spite of the criticisms to which meters might be open, the people responsible for their design had certainly stimulated interest in the visibility problem.

APPLICATIONS FOR MEMBERSHIP.

Elections Pending.

The names of the following applicants for membership were presented for the first time at the General Meeting on Tuesday, April 9:—

CORPORATE MEMBERS:—

Brown, E. R. ..... 100, Heeley Bank Road, SHEFFIELD 2.
Cooper, H. ..... Messrs. T. B. Morley and Co., Ltd., Jameson Street, HULL.
Dickson, C. F. ..... Messrs. Crompton Parkinson, Ltd., Bush House, Aldwych, LONDON, W.C.2.
Eddison, G. ..... Ivyville, Vinery Road, Burley, LEEDS 4.
Friend, D. R. ..... 2, Elms Drive, Kirkella, HULL.
Hailstones, F. ..... 75, Bath Road, GLASGOW C.2.
Harrison, T. H. ..... 20, Gloucester Road, KINGSTON-ON-THAMES.
Hobley, F. R. ..... 131, Brookland Road, BRIDLINGTON.
Marshall, C. R. ..... Electricity Offices, Hatfield, HERTS.
Miller, J. F. ..... 19, Sunningdale Road, Hessle, E. YORKS.
Stephen, J. F. ..... 86, Firs Drive, Cranford, MIDDX.
Tillotson, G. S. ..... 318, Birchnell Avenue, HULL.
Thompson, H. L. ..... 558, Beverley High Road, HULL.
Warburton, J. F. ..... 3, Agnes Road, Blundellsands, LIVERPOOL 3.

COUNTRY MEMBERS:—

Heydon, V. ..... 197, Lichfield Road, Four Oaks, SUTTON COLDFIELD.
Presnall, A. C. ..... 26, Warneford Gardens, Chanterland Avenue, HULL.

Elections Completed.

At this meeting the names of those announced on February 13, which were published in "The Transactions" (Vol. V., No. 2, 1940, p. 31), were presented again, and these applicants were formally declared members of the Society.

ANNUAL GENERAL MEETING

The Annual General Meeting, to be followed by an ordinary sessional meeting, will take place at the E.L.M.A. Lighting Service Bureau, 2, Savoy Hill, London, W.C.2, on Tuesday, May 7, 1940, when the proceedings will be as follows:—

5.30 p.m. Light Refreshments will be provided.

6 p.m. The Annual Report of the Council and Statement of Accounts for the past year will be submitted and the usual Resolutions approving their adoption and the appointment of Auditors for the coming year will be put to the meeting.
Thereafter the usual formal business of sessional meetings will be transacted, and the following papers will be read and discussed:—
The New Unit of Light by J. W. T. WALSH, M.A., D.Sc., M.I.E.E.
The Colour Sensitivity of the Human Eye by J. S. PRESTON, M.A., F.Inst.P., and **The Physical Realisation of the C.I.E. Average Eye** by G. T. WINCH and C. F. MACHIN.

INFORMAL LUNCHEON

An **Informal Luncheon** has been arranged to take place at **St. Ermin's Hotel,** Westminster, at **1 p.m.,** on Tuesday, **May 7.** Attendance will be confined to members of the Society.

Tickets (Price 5s. 6d. each) may be obtained on application to the Hon. Secretary.

As the space available is limited early application for tickets is advised.

NOTES ON RECENT MEETINGS AND EVENTS

General Meetings in London.

A general meeting was held in the lecture theatre of the E.L.M.A. Lighting Service Bureau (2, Savoy-hill, Strand, London, W.C.) on April 9. The chair was taken by the President at 6 p.m., and a paper entitled "The Photometric Properties of Luminescent Materials," by Mr. W. E. Harper, Miss Margaret B. Robinson, and Mr. J. N. Bowtell, was presented.

The paper was illustrated by numerous lantern slides and demonstrations, and led to an interesting discussion in which the following took part: Dr. C. C. Paterson, Dr. J. W. T. Walsh, Dr. T. H. Harrison, Mr. J. Edwards, Mr. A. D. Harris, Mr. J. S. Preston, Mr. J. S. Dow, Mr. P. Good, Mr. H. E. Beckett, Mr. S. J. Patmore, Mr. R. Pelerin, Mr. R. Brewer, and Mr. E. W. Murray.

After reply had been made to the discussion a vote of thanks to the authors of the paper and to the E.L.M.A. Lighting Service Bureau for their hospitality terminated the proceedings.

Members of the Society also participated in a joint meeting with the Road and Building Materials Group of the Society of Chemical Industry, which was held at Burlington House, London, on April 2.

A discussion on "Road Surfaces and their Influence on Street Lighting" was opened by Mr. J. M. Waldram, who illustrated his remarks by numerous slides illustrating the effect of various methods of lighting and the condition of road surfaces on the resultant distribution of brightness. A keen discussion ensued, in which members of both bodies took part, and at close of the meeting a cordial vote of thanks was moved to Mr. J. M. Waldram for his paper.

North Midland Local Centre.

A general meeting of the North Midland Area Local Centre was held on Monday, March 11, 1940, at the Electricity Showrooms, Leeds, when a paper on "Commercial and Decorative Lighting" was read by Mr. C. W. M. Phillips, A.M.I.E.E.

The speaker, who showed lantern slides of interest displaying the methods to be adopted in dealing with various situations, also explained precautions to be adopted in the design of installations with a view to prevent glare and producing the special "atmosphere" necessary in some cases. The main portion of the paper dealt with the new 80 watt fluorescent 5 ft. tube, and contained comparisons with existing mercury and fluorescent lamps.

The author was later thanked for his paper by the Chairman (Mr. J. W. Howell) and was complimented on the able manner in which he answered the many questions on the construction and physical properties of the new lamp.

Meetings Devoted to War Time Street Lighting.

Further opportunities of explaining the nature and objects of war time street lighting have been afforded at meetings of the Society in Nottingham on January 12 and in Glasgow on February 16. At both centres the President reviewed recent work on A.R.P. lighting carried out for the Joint Committee, devoting special attention to the specification of war time street lighting (BS/ARP 37), which had been the subject of a series of special meetings in London.

Mr. F. Walker presided over the meeting in Nottingham when Mr. Smith's address was followed by a paper by Mr. J. Bertram on "The Utility Value of Low Levels of Illumination," leading to an interesting discussion in which Professor H. Cotton, Mr. Howard Long, and others took part.

Mr. E. J. Stewart presided over the meeting in Glasgow, where the audience, approaching 200, included many representatives of local authorities in the vicinity. Arrangements were made for specimens of war time street lighting units, both gas and electric, to be on exhibition in the lecture theatre, and visitors had an opportunity of inspecting adjacent streets in which war time street lighting had been installed.

Meetings in Birmingham and Nottingham.

Other events have taken place in Birmingham, where an informal dinner was arranged by the Midland Local Centre on March 1, and in Nottingham where, on January 12, Mr. Howard Long delivered an address on "Planned Lighting for Seeing," and on March 13 Mr. R. O. Ackerley lectured on "Special Industrial Lighting." Both papers in Nottingham led to a keen discussion, and this newly formed subcentre is to be congratulated on arranging a series of meetings in spite of war time conditions.

The informal dinner held in Birmingham on March 1 served the purpose of bringing members together. Dr. F. S. Ette, chairman of the Centre, presided. The President and Hon. Secretary of the Society journeyed from London in order to attend the gathering, and the former gave an address in which he briefly reviewed recent developments in London and expressed the interest of the Council in the progress of the various Local Centres.

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REPORT OF THE COUNCIL FOR THE SESSION OCTOBER, 1939 TO MAY, 1940

(Presented at the Annual General Meeting, which took place at the E.L.M.A. Lighting Service Bureau (2, Savoy Hill, London), at 5.30 p.m. on Tuesday, May 7th, 1940.)

During the past session the Society has been called upon to meet very exceptional conditions. Following the outbreak of war an emergency meeting of the Council was called. It was agreed that every effort should be made to maintain the organisation and activities of the Society, which it was felt should prove of considerable national value both during hostilities and in the subsequent period of reconstruction. It was decided that the affairs of the Society should continue to be conducted from its offices in London, that the regular issue of publications should be continued, but that no formal programme of events should be issued, arrangements in regard to meetings being postponed until the position would become clearer.

It has subsequently been found possible to hold quite a number of meetings, both in London and in provincial cities, and to maintain the activities of the Society with a considerable degree of success.

Even before the outbreak of hostilities the Society had offered its services to the authorities and the opportunities of making use of the expert knowledge of its members were already being explored. During the period following the outbreak of war full use was made of these services, and on several occasions appreciatory acknowledgment of their utility has been made. Further reference is made below to these researches, which have formed the subjects of addresses delivered by the President on several occasions.

Election of Officers and Council for Next Session.

In accordance with the procedure outlined in the Articles and By-Laws of the Society, the nominations made by the Council to fill vacancies have been printed in the "Transactions" of the Society, and corporate members have thus been afforded an opportunity of making additional nominations, if they so desired. No nominations having been received, the proposals of the Council stand.

Accordingly, Professor J. T. MacGregor-Morris will become President, Mr. R. O. Ackerley continuing in office as vice-president, whilst Dr. H. Buckley and Mr. E. J. Stewart will become the new vice-presidents. Mr. J. S. Dow will continue to act as honorary secretary, and Mr. E. W. Murray will continue to act as honorary treasurer.

The following members will fill vacancies on the Council: Mr. R. W. Daniel, Mr. G. Dixon, Mr. N. V. Everton, Mr. G. W. Golds, Mr. Howard Long, Mr. R. Maxted, Mr. C. W. M. Phillips, Mr. E. Stroud, and Mr. J. M. Waldram.

In making these nominations the Council has been influenced by the exceptional conditions now prevailing. In view of the new responsibilities which he had undertaken, the senior vice-president, Mr. W. J. Jones, felt that it would be to the advantage of the Society to defer his term of office as President until the full benefit of his services in the presidential chair could be obtained. Similarly, Colonel C. H. Silvester Evans, owing to his military duties at present making it impossible to devote attention to the affairs of the Society, has tendered his resignation from the vice-presidency. These considerations induced the Council to invite Professor J. T. MacGregor-Morris to accept the presidency for the coming Session, and they record with great satisfaction that he has kindly consented to do so, and to nominate Dr. H. Buckley and Mr. E. J. Stewart to fill the two vacancies created in the list of vice-presidents.

Appointment of Committees.

In view of the uncertain outlook following the outbreak of war and the demands now made upon the services of many members for special work on A.R.P. lighting, the operations of the ordinary standing committees have been to some extent in abeyance.

The *General Purposes Committee* was constituted in the customary manner as follows: Mr. F. C. Smith (president), Mr. J. S. Dow (hon. secretary), Mr. E. W. Murray (hon. treasurer), Dr. S. English (past president), Mr. P. Good (past president), Mr. W. J. Jones and Col. C. H. Silvester Evans (vice-presidents).

In view of the fact that several of the above would probably be unable to attend meetings constantly, it was resolved to strengthen the committee by the co-

option of Mr. R. O. Ackerley, the remaining vice-president, and Mr. A. Cunnington and Mr. E. Stroud, the remaining members of the General Purposes Committee, for the Session 1939-1940. The committee thus constituted has served as an *Executive Committee*, dealing with all essential questions but reporting to the Council at suitable intervals.

The *Papers Committee* was constituted as follows: Mr. G. H. Wilson (chairman), Col. C. H. Silvester Evans, Mr. C. E. Greenslade, Mr. J. S. Preston, and Dr. J. W. T. Walsh.

As soon as it became evident that a certain number of meetings could advantageously be arranged this committee commenced to function, and it has been instrumental in arranging a number of interesting events.

Researches on A.R.P. Lighting.

The outbreak of war and the consequent lighting restrictions have naturally limited severely many fields of lighting activity. The prohibition of all outside lighting—except to the limited extent sanctioned by special regulations—has brought to a stop normal developments. Even in the case of interior lighting, on which no limits have been set by the authorities provided a satisfactory "black out" is achieved, developments have naturally been restricted in comparison with normal times.

There has, however, been ample opportunity for the utilisation of the expert knowledge of illuminating engineers in the application of these restrictions and in ensuring that the best possible use is made of the small amount of light permissible. Shortly before the war the Society came into contact with the Ministry of Home Security, with the result that a joint committee—on which leading officials of the Ministry and members of the Society conferred, on which the Association of Public Lighting Engineers are also represented—was formed, with Mr. Percy Good as chairman. Those associated with the Ministry have done everything possible to facilitate the researches since initiated, and on several occasions have testified to the utility of the work accomplished.

In the future it will doubtless be possible to give a much fuller account of this work, which has engaged the attention of about twenty-four sub-committees and of approximately 100 members of the Society, and has already involved the expenditure of many thousands of "man-hours" of effort.

The President's address, delivered at the opening meeting of the Society, in London, on November 14, and his subsequent addresses at meetings of Local Centres have contained surveys of this work. Amongst the problems investigated have been Fittings to Furnish Low Illuminations (0.002, 0.02, and 0.2 ft.c.), the Comparative Advantages of Blue and White Light, Light Traps for Entrances to Buildings, A.R.P. Signs, Luminescent Materials, Photometric Gauges for Checking Low Illuminations, Masks for Motor Car Headlights, War Time Shop-Window Lighting, and War Time Street Lighting.

Decisions were frequently in urgent demand, and experiments were necessarily conducted at high pressure. In a number of cases, however, the researches have already led to the issue of British Standard Specifications, the contents of which have been made known to members, as they appeared, through the publications of the Society.

The researches on war time street lighting, which have led to the issue of the British Standard Specification (BS/A.R.P. 37) defining the conditions to be complied with by war time street lighting units, have naturally excited much public interest. It has fallen to the Society both to undertake the initial experimental work and to participate in arrangements organised by the Joint Committee for the purpose of introducing this form of lighting to the public. The prolonged and careful investigations, correlating experience of conditions on roadways lighted to various degrees of illumination with aerial observations, have been such as to satisfy the authorities that the low level of illumination prescribed (0.0002 ft.c.) is the most that can safely be permitted for continuous and permanent lighting in war time. It has been possible to demonstrate, however, that under present conditions this illumination has considerable amenity value, whilst in the event of air raids its existence should prove of vital importance.

The Specification was brought to the notice of public lighting authorities at a special meeting held at the Caxton Hall, Westminster, on December 18, 1939, and again at a series of meetings at the Empire Restaurant, Westminster, on three successive evenings, February 6, 7, and 8, 1940, during which tours of inspection of adjacent streets already furnished with the system of war time street lighting took place. In arranging these meetings the Society received most helpful co-operation from the Association of Public Lighting Engineers.

General Meetings in London.

As explained earlier, it was thought expedient, at the opening of the Session, to await some clarification of the general position before any meetings were

arranged. The customary Presidential Address was accordingly deferred, but at the opening meeting, eventually arranged on November 14, the President addressed members of the Society, explaining the intentions of the Council and giving some account of the investigations on A.R.P. Lighting, already rapidly developing. At this meeting, which was held in the lecture theatre of the E.L.M.A. Lighting Service Bureau, Mr. W. J. Jones arranged several exhibits illustrating certain aspects of this work, and Lt.-Col. Kenelm Edgcumbe and Mr. G. E. V. Lambert exhibited gauges for checking low illuminations.

A paper on "Discomfort Glare in Lighted Streets" was read by Mr. Ralph G. Hopkinson, at a meeting held on January 9, and was followed by a keen discussion. On February 13 a very successful informal meeting devoted to "Photometric Reminiscences" was held at St. Ermin's Hotel, Westminster, in the course of which reminiscences were contributed by Dr. C. C. Paterson, Mr. G. H. Wilson, Mr. E. Stroud, Mr. P. J. Waldram, Mr. F. C. Smith, Dr. J. W. T. Walsh, Mr. W. J. A. Butterfield, Lt.-Col. Kenelm Edgcumbe, and a number of other members.

To the general regret Mr. A. P. Trotter was unable to attend this meeting, and his contribution, summarising experiences during the past fifty years, was read to those present.

On April 9 a paper entitled "The Photometric Properties of Luminescent Materials," by Dr. W. E. Harper, Miss Margaret B. Robinson, and Mr. J. N. Bowtell, was read, and on April 23 members took part in a meeting at Watson House where, after inspection of the laboratories, a paper by Mr. L. T. Minchin, Mr. A. B. Densham, and Mr. J. Wright on "Some Physical Problems Associated with Gas Lighting" was presented.

The Council desire to express their appreciation of the hospitality of the Gas Light and Coke Company in connection with this meeting, and likewise of the hospitality of the E.L.M.A. Lighting Service Bureau, in whose lecture theatre several meetings of the Society were held—a fortunate arrangement in the present circumstances when, owing to war time conditions, the lecture theatres of various scientific and technical bodies were not available.

Members of the Society also participated in a meeting arranged by the Society of Chemical Industries on April 2, when a discussion on Road Surfaces and Their Influence on Street Lighting was initiated by Mr. J. M. Waldram.

The attendance and interest shown in these various gatherings fully justified the decision to resume regular meetings. In view of the prevailing conditions, and the demands made on the time of many members for special war work, it was, however, decided not to arrange any Sectional Meetings.

Two departures have been made in the arrangements for the Annual General Meeting on May 7. In view of the difficulty in securing a lecturer from abroad under present conditions, three papers reviewing important recent developments in Photometry by Dr. J. W. T. Walsh ("The New Unit of Light"), Mr. J. S. Preston ("The Colour Sensitivity of the Human Eye"), and Mr. G. T. Winch and Mr. C. F. Machin ("The Physical Realisation of the C.I.E. Average Eye"), have been arranged to follow the transaction of formal business.

In addition, an informal luncheon has been arranged to take place on that day at St. Ermin's Hotel as a substitute for the customary annual dinner.

The Leon Gaster Memorial Fund.

The Leon Gaster Premium of ten guineas was awarded to Mr. H. Warren for his paper entitled "Research on the Production and Utilisation of Light," read at the meeting of the Illuminating Engineering Society on February 14, 1939.

No applications have been received for the Silver Jubilee Commemoration (1934) Award. Future arrangements in connection with this award are now under consideration.

North Midland Area Local Centre.

The Committee of this Local Centre, which last year requested and received formal recognition, was among the first to resume activities after the outbreak of war.

The local Committee was constituted as follows: Mr. J. W. Howell (chairman), Mr. H. C. Elliott, Mr. F. Firth, Mr. J. D. Green, Mr. W. Hetherington, Mr. W. I. Ineson, Mr. E. Lunn, Mr. H. Peters, Mr. W. F. Pogson, Mr. H. O. Seville, Mr. J. S. Shaw, and Mr. A. Wilde. Mr. T. C. Holdsworth (hon. secretary).

The Centre has organised a number of successful meetings. At the opening meeting on December 11 an address was given by the President, and an exhibition of lighting apparatus took place. On January 8 a discussion on "The Lighting Requirements in the Factory Act" was initiated by Mr. F. Baker, Mr. A. E. Iliffe, and Mr. R. W. Daniel. On February 12 an address on "The Maintenance of a Factory Lighting Installation" was given by Mr. H. Fletcher, and was followed by a keen discussion. The final meeting, on March 11, was devoted to a paper

by Mr. C. W. M. Phillips on "Commercial and Decorative Lighting."

The accompanying statement reveals that the expenditure for the year was considerably below the prescribed allowance. This is due partly to the economical manner in which the affairs of the Centre have been conducted and partly to the fact that the number of meetings has been diminished. In normal years expenditure on additional meetings, including those of sub-centres, will have to be met, but there appears every reason to anticipate that this official Centre will continue to prove itself self-supporting.

address by Mr. R. O. Ackerley on "Special Industrial Lighting Problems." Through the efforts of the committee and the hon. secretary, Mr. C. S. Caunt, the sub-centre has already collected a nucleus of over sixty members.

The Scottish Local Centre (chairman, Mr. E. J. Stewart; hon. secretary, Mr. M. W. Hime) with headquarters in Glasgow, held a very successful meeting on February 15, when the President once more gave an address on the A.R.P. Lighting investigations, dwelling especially on the recently introduced wartime street lighting, of which examples were on view in neighbouring streets. The audience, which

NORTH MIDLAND AREA LOCAL CENTRE—STATEMENT OF INCOME AND EXPENDITURE, 1939.

Balance at Local Centre			10	12	7
Cash received from Headquarters			20	0	0
Provision for Expenditure in respect of Subscriptions paid by Members of Local Centre...	62	7	6		
Less Remittance (as above)	20	0	0		
Amount unexpended			42	7	6
			£73	0	1

Expenditure (Printing, Postage, Stationery, etc.)				19	13	0
Balance—						
In hand at Local Centre	10	19	7			
Amount unexpended	42	7	6			
				53	7	1
				£73	0	1

The formation of a sub-centre in Sheffield, with Mr. H. Wheeler as chairman and Mr. J. H. Campbell as hon. secretary, and with a membership of about thirty, has already resulted in a useful addition to the ranks of the Society, and has several meetings in prospect. It is now proposed to establish a similar sub-centre in Hull, where a committee, with Mr. J. W. Rattle as chairman and Mr. H. B. S. Franks as hon. secretary, has recently been formed.

Informal Local Centres.

The Midland Local Centre (chairman, Mr. F. S. Ette; hon. secretary, Mr. A. E. B. Wallis) initiated its programme on March 1, when an informal dinner, over which the chairman presided, was held in Birmingham. This dinner was effective in bringing members together and prospective arrangements for the holding of several subsequent meetings were announced. The President and hon. secretary of the Society attended from London, and the former gave a brief account of recent work on A.R.P. Lighting.

The President also addressed the newly formed sub-centre in Nottingham, the chairman, Mr. F. Walker, presiding. At a subsequent meeting on February 9 Mr. Howard Long, who was so largely instrumental in the formation of this sub-centre, gave an address on "Planned Lighting for Seeing." The final meeting, on March 15, was devoted to an approached 200, contained numerous representatives of neighbouring local authorities, and keen interest in these developments was expressed.

Of the remaining centres, that in the North-Western Area has apparently suffered through the absence of its chairman (Mr. R. C. Hawkins) on active service and no reports of meetings have been received. The Local Centre for Eire, with headquarters in Dublin, is in abeyance.

Relations with Local Centres.

It is satisfactory to record that, in spite of the disturbance arising from war, the Local Centres have been able, in the main, to preserve their organisations and to resume their activities. In several instances the committees have rendered useful assistance in connection with researches on A.R.P. lighting problems initiated in London.

The Council attaches great importance to the maintenance of close relations with the various Local Centres and the encouragement of their participation in the conduct of the affairs of the Society. The chairman of the North Midland Local Area, which is now formally constituted, is *ipso facto* a member of the Council in accordance with Article 41. But in the case of the other informal Local Centres it is also the practice to invite the presence of chairmen (without voting power) at Council

meetings, in order that links with all areas may be established. In addition, it is to be noted that the list of new members of Council contains the names of several who are attached to Local Centres —whose committees are invited to send in suggestions for nominations, which are normally considered in February. Their attention is also drawn to the practice now adopted by the Council of placing the item "Local Centres" as a permanent feature on their agenda, so that an opportunity to consider their activities and any questions of interest to them may be afforded at each Council meeting.

Arrangements are also being made to continue the annual conferences with representatives of Local Centres initiated for the first time last Session, and a meeting is being called for the afternoon of Tuesday, May 7, following the informal luncheon.

The Transactions.

After careful consideration it was decided at the outbreak of war to continue the regular issue of "The Transactions" in its present form. The regular publication of "Light and Lighting" has also been continued. It is felt that the maintenance of these channels of information is particularly valuable at present, when intercourse between members is less easy than in normal times.

Papers and addresses presented at general meetings, and two papers presented at Sectional Meetings (that by Mr. F. X. Algar, before the Street-Lighting Section, on "Two New Public Lighting Installations in Dublin," and that by Mr. C. Dunbar, before the Photometry Section, on "Fundamental Principles of Meters Used to Measure Visibility") have been published.

In addition, publicity has been given to several communications of technical interest, namely, "Visual Efficiency in Coloured Light," by C. Dunbar; "Light Scattering by Road Surfaces," by A. Bloch; and "Daylight Factors for Efficient Working and their Predetermination," by T. C. Angus.

Publication in "The Transactions" of some of the most important British Standard Specifications dealing with A.R.P. Lighting has also proved of great value in making this information known to members of the Society.

Membership.

Since the commencement of the new session upwards of 100 new members have been added to the list. For this increase the formation of new subcentres, initiated before the outbreak of war, has been mainly responsible. Subsequently there have, as is natural in the circumstances, been a number of resignations and also numerous cases of members whose present addresses cannot be traced, or who are known to be on active service and whose membership must be regarded as in suspense. There is, however, every indication that the interest in the Society of members as a whole has in no way diminished, and that the number mentioned in the last report (950) will at least be maintained. Ultimately it is believed that the restrictions on lighting, by impressing on the public mind the vital importance of light as a commodity and directing attention to the essential elements of good lighting, should tend to stimulate interest in the Society's work and enhance its prestige.

The Council records with regret the death of several members of long standing. Sir Francis Goodenough was one of the founder members of the Society, of which he became President in 1931. Dr. R. J. Lythgoe was recently a Member of Council. Mr. H. W. Gregory had been associated with the Society for a number of years. By the death of Mr. L. B. Marks, past president of the Illuminating Engineering Society in the United States, the Society loses the last of its representatives in other lands nominated honorary members in view of their distinguished services to illuminating engineering.

Status Grade of Membership.

The Council has devoted much attention to the preparation of a scheme for Status Grade of Membership as outlined in the Report for the previous Session. The proposed scheme, it will be recalled, does not impose any new conditions on those desiring to enter the Society. The scheme does, however, make it possible for those members who desire recognition of their technical qualifications to apply for a special distinction, such as the title "Fellow," which would carry with it the right to the use of the letters "F.I.E.S."

The adoption of the scheme in itself necessitates revision of the by-laws of the Society. The opportunity was, therefore, taken, when inserting new clauses embodying the scheme of Fellowship, to make certain changes in keeping with developments that have occurred during the ten years that have elapsed since the by-laws were originally drafted.

The new by-laws were circulated to all Corporate Members and received their approval at an Extraordinary General Meeting held on December 5. The approval of members having thus been secured, the next step was to explore more fully the legal position. In this connection expert advice has been taken and the position very carefully studied. The

latest expert information appears to confirm the view held by the Council that the proposed changes contemplated are in no way at variance with the Memorandum and Articles of the Society. Accordingly, no change in the Memorandum appears requisite, and in regard to the Articles there is no necessity for any alteration at the moment, though the Council may propose certain additions and modifications at a later date, when experience has been gained of the operation of the Fellowship scheme, in order to record its existence and to give effect to certain other alterations in procedure, on which the approval of members would first be solicited.

The initial Board of Fellows has now been constituted in accordance with the new by-laws, and the Board is preparing rules of procedure. The necessary forms of application have also been prepared. An announcement will be made shortly inviting members who so desire to apply for Fellowship. It is anticipated that a list of Fellows will be issued before the commencement of 1941, and that the scheme will be in full operation from that date onwards. In the meantime, the amended by-laws are being subjected to final scrutiny with a view to finding any possible discrepancies in detail The final version will be published in due course in The Transactions of the Society.

Examinations in Illuminating Engineering.

The holding of the first Intermediate Examination in illuminating engineering by the City and Guilds of London Institute for 1939 was encouraging in revealing an evident demand for this new venture and a fair degree of proficiency on the part of those who entered. There were in all twenty-nine candidates of whom nine passed in the first class and thirteen in the second. The majority of the candidates entered from educational institutions in London, but there were also entrants from provincial cities, and one from New Zealand. It is satisfactory to observe the Institute has determined to repeat the examination during the present year.

Financial Position.

The accounts for the past year, which are attached, reveal an encouraging position, in view of the unprecedented conditions which the Society has been experiencing. It will be observed that the income from subscriptions during the past year increased by approximately £146—a result which is largely due to the additional subscriptions received from new members in Local Centres and to the change from Country Members to full Corporate Membership of the majority of members connected with the Official Centre for the North Midland Area. Expenditure in certain directions has diminished, partly owing to the diminution in the number of meetings held, with the result that a surplus of income over expenditure of £334 19s. 2d. is shown. Out of this surplus £250 National Defence Bonds have been purchased and appear in the list of investments in the balance-sheet.

It will be observed that some utilisation has been made of contributions from the National Illumination Committee and the International Illumination Congress Funds in order to meet the expenses of delegates to the Congress of the International Commission on Illumination in Holland. With a view to avoiding sales of war stock held for both Funds a temporary overdrawing of these accounts was sanctioned. The deficits have, however, already almost been counterbalanced by the interest since received and should be completely eliminated in the course of the present session.

Relations With Other Bodies.

As explained previously, a considerable number of members have been engaged in arduous researches on A.R.P. lighting conducted for the Joint Committee with which the Society is associated. Throughout this work the close association maintained with the British Standards Institution, whose Deputy-Director, Mr. Percy Good, is chairman of the Joint Committee, has proved of inestimable value.

Members of the Society are continuing to serve on the Departmental Committee formed by the Home Office dealing with Factory Lighting, whose interim Report was issued in November, 1938, and to take an active part in the work of other organisations interested in illumination. The Society appoints annually representatives to serve on the National Illumination Committee. A considerable number of its members also serve on the various committees operating under the National Illumination Committee, the British Standards Institution, and the Department of Scientific and Industrial Research.

International Commission on Illumination.

The Society was well represented at the tenth meeting of the International Commission on Illumination held in Holland during June 12 to 20. A variety of subjects was dealt with, and over fifty reports and papers were presented and discussed at the technical sessions. A number of important decisions were taken. Few could have anticipated the events which have followed so closely on

the termination of this conference, at which representatives of the leading countries of the world conferred in harmony. We can only look forward to the ultimate resumption of these international relations in the field of illumination. It had been intended that a survey of the conference would form the main subject of the Presidential Address. It is hoped that this review is only deferred. Meantime an account of the proceedings was published in "Light and Lighting" (July, 1939).

Programme for the Next Session.

The demand for the services of members in connection with special lighting problems arising through the war will doubtless continue, and will probably extend. Nevertheless, it is hoped that it will be still possible to retain the normal activities of the Society and to prepare a useful programme of meetings for the forthcoming session. The Council desire to take this opportunity of thanking the many members who have assisted in the arduous work of committees or are undertaking secretarial duties. Offers of help in connection with these various services will be welcome, and papers and suggestions in regard to meetings are invited. Wherever possible authors of papers are asked to prepare manuscripts in good time before the opening of the session in October next, so that ample time may be available to allot dates, and to take any measures necessary to ensure informative and successful meetings.

F. C. SMITH.
(*President.*)

JOHN S. DOW.
(*Hon. Secretary.*)

INCOME AND EXPENDITURE ACCOUNT FOR THE YEAR ENDED 31st DECEMBER, 1939.

Dr. EXPENDITURE.

	£ s. d.	£ s. d.
To Administration Expenses:—		
Rent and Clerical Assistance ...	250 0 0	
Printing, Stationery, etc.	136 16 7	
Duplicating	78 18 0	
Postage and Office Expenses... ...	109 7 11	
General Meetings in London:— £ s. d.		
Hire of Halls 22 11 6		
Reporting and Lantern Operating 24 3 0		
Refreshments 19 0 8		
	65 15 2	
Special Meeting (A.R.P. Lighting):—		
Cost of Hall, Transport and Refreshments ... £ s. d. 34 10 11		
Less Receipts 15 11 0		
	18 19 11	
Sectional Meetings in London	46 3 8	
Local Centres:—		
N. Midland Centre—		
Provision of £ s. d.		
Subscriptions 62 7 6		
Less unexpended... 42 7 6		
20 0 0		
Remittances to other Centres for Expenses of Meetings... ... 66 13 6		
	86 13 6	
Bank Charges	1 15 0	
Audit Fee	10 10 0	
		804 19 9
,, Cost of Printing Transactions, Reprints, Blocks, etc.	329 16 1	
Less Sales of Reprints	112 10 1	
		217 6 0
,, Illuminating Engineering Publishing Co., Ltd.:— Allocation and Share of Subscriptions		430 19 0
,, National Illumination Committee		32 0 0
,, British Standards Institution		10 10 0
,, Premium on Deferred Annuity to Staff		38 15 3
,, Honorarium to Staff		15 10 0
,, Excess of Income over Expenditure		334 19 2
		£1,884 19 2

INCOME. *Cr.*

	£ s. d.	£ s. d.
By Subscriptions		1,778 2 0
(Including Two Life Subscriptions of £15 15s. each)		
,, Subscriptions Outstanding (Estimated)		20 0 0
,, Interest on War Stock		52 10 0
,, Bank Interest		3 18 10
,, Sundries, Subscriptions to Transactions, etc. ...		14 9 6
,, Annual Dinner—		
Receipts £255 0 0		
Less Payments 239 1 2		
		15 18 10
		£1,884 19 2

The statement of the Auditors certifying these accounts will be found at the foot of the following page.

BALANCE SHEET, 31st DECEMBER, 1939.

LIABILITIES.	£ s. d.	£ s. d.	ASSETS.	£ s. d.	£ s. d.
Creditors		32 11 3	Cash at Bank		322 8 6
Subscriptions paid in advance		4 4 0	Cash in hand		10 6 10
Capital Account:—			£1,500 3½ per cent. Registered War Stock at cost		1,559 15 0
Balance per last Account	1,803 17 5		*(Value on Dec. 31st, 1939, £1,395)*		
Add Excess of Income over Expenditure for the year	334 19 2		£250 National Defence Bonds at cost		250 0 0
		2,138 16 7	Subscriptions Outstanding		20 0 0
			Sundry Debtors on Sales Transactions		13 1 6
		£2,175 11 10			£2,175 11 10

LEON GASTER MEMORIAL FUND ACCOUNT, 31st DECEMBER, 1939.

	£ s. d.	£ s. d.		£ s. d.	£ s. d.
Fund at the beginning of the year		243 0 4	Expended during the year:—		
War Stock Interest		8 1 0	Premium for 1939/40		10 10 0
			Balance:—		
			Cash at Bank	3 18 2	
			Invested in £230 3½ per cent. Registered War Stock at cost	236 13 2	
			(Value on Dec. 31st, 1939, £214)		240 11 4
		£251 1 4			£251 1 4

LIBRARY FUND ACCOUNT, 31st DECEMBER, 1939.

	£ s. d.		£ s. d.
Balance at the beginning of the year	21 14 6	Balance:—	
		Cash at Bank	21 14 6
	£21 14 6		£21 14 6

NATIONAL ILLUMINATION COMMITTEE FUND, 31st DECEMBER, 1939.

	£ s. d.	£ s. d.		£ s. d.	£ s. d.
Fund at the beginning of the year		367 0 1	Allocation to Expenses of Delegates at I.C.I. Congress		80 0 0
War Stock Interest		10 10 0			
Deposit Interest		2 8	Balance:—		
			£300 3½ per cent. Registered War Stock at cost	304 8 6	
			(Value on Dec. 31st, 1939, £279)		
			Less Overdraft at Bank	6 15 9	
					297 12 9
		£377 12 9			£377 12 9

INTERNATIONAL ILLUMINATION CONGRESS FUND (1931), 31st DECEMBER, 1939.

	£ s. d.	£ s. d.		£ s. d.	£ s. d.
Fund at the beginning of the year		336 15 0	Allocation to Expenses of Delegates at I.C.I. Congress		45 0 0
War Stock Interest		10 10 0			
			Balance:—		
			£300 3½ per cent. Registered War Stock at cost	304 8 6	
			(Value on Dec. 31st, 1939, £279)		
			Less Overdraft at Bank	2 3 6	
					302 5 0
		£347 5 0			£347 5 0

We have examined the above accounts with books and vouchers, and certify same to be correct in accordance therewith, and that the Balance Sheet exhibits a true and correct view of the Society's affairs according to the information and explanation given to us.

Dated this 14th day of March, 1940.

ROBERT J. WARD & CO., *Chartered Accountants*,
40, Chancery Lane,
London, W.C.2.

NOTES ON RECENT MEETINGS AND EVENTS

General Meetings in London.

A Sessional Meeting of the Society was held at the invitation of the Gas Light and Coke Company, at Watson House, on **Tuesday, April 23, 1940.** Before the meeting commenced visitors were afforded an opportunity of passing through the laboratories, in the course of which much interesting apparatus was examined and numerous researches in progress were explained. The processes witnessed included research on the bunsen burner and methods of determining the air-gas ratio, the catalytic ignition of gas, the use of the integrating radiometer for the determination of radiant efficiency of gas-fires, etc., the testing of industrial equipment, and the photometric testing of war-time street-lighting fittings.

After members had inspected the laboratories the chair was taken by the President at 6.30 p.m. The minutes of the last meeting, which had been circulated, were taken as read. The Honorary Secretary reported the name of Mr. W. G. A. Taylor, of the National Physical Laboratory, Teddington, as an applicant for membership, and the names of those announced at the previous meeting were now formally declared members of the Society.

The president then called upon Mr. L. T. MINCHIN, Mr. A. B. DENSHAM, and Mr. J. WRIGHT to present their paper, entitled "Some Physical Problems Associated with Gas Lighting." The paper was illustrated by lantern slides and experiments, some of which were repeated later on during the meeting at the desire of the audience. The discussion was opened by Mr. C. A. Masterman, who conveyed a welcome to visitors on behalf of the Gas Light and Coke Company, and was continued by Mr. J. Benton, Mr. G. H. Wilson, Mr. J. S. Dow, Mr. S. S. Beggs, and Dr. S. English. A communication was read from Mr. E. C. Smith, of Leeds University. A vote of thanks to the authors and to the Gas Light and Coke Company for their hospitality was proposed by Mr. G. H. Wilson, and carried with acclamation.

A Sessional Meeting following immediately after the Annual General Meeting (see p. 54) took place at the E.L.M.A. Lighting Service Bureau (2, Savoy-hill, London, W.C.) on **Tuesday, May 7.**

After the transaction of formal business, the President called upon Dr. J. W. T. WALSH to present his paper on "The New Unit of Light." The paper traced efforts made from the early years of the present century onwards to establish the "international candle," the subsequent researches leading to the new black-body absolute standard of light, and the agreement reached on the "new candle," the introduction of which had unfortunately been deferred owing to the outbreak of war.

Mr. J. S. PRESTON, who for official reasons had been unable to present his paper as anticipated, then gave an interesting demonstration of the Purkinje and field size effects. This was achieved in an ingenious manner by the use of a screen divided into two rectangles coated with materials fluorescing respectively red and blue when irradiated by a "black" lamp, the distance of which from the fluorescing material could be progressively varied. (It is hoped that Mr. J. S. Preston's paper will appear in "The Transactions" in due course.)

A paper by Mr. G. T. WINCH and Mr. C. F. MACHIN, entitled "The Physical Realisation of the C.I.E. Average Eye," was next presented. The authors first gave a brief historical survey of previous attempts to realise a physical eye of defined spectral sensitivity, and subsequently described and illustrated an apparatus developed by them for use as an "average eye" as defined by the C.I.E. Such an apparatus may be used as a physical colorimeter and as an instrument for measuring spectral luminosity. It has also possible applications to commercial photometry, colorimetry, and colour-rendering measurements.

In the ensuing discussion Mr. G. H. Wilson, Dr. C. C. Paterson, Mr. M. G. Bennett, Dr. J. W. T. Walsh, Mr. J. S. Preston, and Mr. J. M. Waldram took part. A vote of thanks to the authors and to the E.L.M.A. Lighting Service Bureau for their hospitality, terminated the proceedings.

APPLICATIONS FOR MEMBERSHIP.

Elections Pending.

The name of the following applicant for membership was presented at the general meeting on Tuesday, May 7:—

CORPORATE MEMBER:—
Duncan, N. L. .....Electricity Offices, Dockfield Shepley, YORKS.

Elections Completed.

At the general meeting on April 23, the names of applicants for membership published in "The Transactions" (Vol. V., No. 3, 1940, p. 43) were presented again, and these gentlemen were formally declared members of the Society.

At the general meeting on May 7, the following applicant, whose name had been previously presented at the general meeting on April 23, was also declared a member of the Society.

CORPORATE MEMBER:—
Taylor, W. G. A. .....National Physical Laboratory, Teddington, MIDDLESEX.

PROCEEDINGS AT THE ANNUAL GENERAL MEETING

(Held on Tuesday, May 7th, 1940.)

The Annual General Meeting of the Illuminating Engineering Society took place in the Lecture Theatre of the E.L.M.A. Lighting Service Bureau (2 Savoy-hill, London, W.C.), on Tuesday, May 7. Members assembled for light refreshments at 5.30 p.m. and the chair was taken by the President at 6 p.m.

The Honorary Secretary having read the notice convening the meeting, the minutes of the last annual general meeting, which had been published, were taken as read and confirmed.

THE PRESIDENT then presented the Report of the Council for the past session. In doing so he remarked upon the difficult period through which the Society was passing, and detailed the steps taken by the Council to maintain its organisation and activities. He expressed his sincere appreciation of the manner in which members had supported the efforts of the Council, and of the wholehearted response to the demands for special work in connection with A.R.P. lighting, the value of which had on several occasions been acknowledged by the authorities. Reference was made to the various successful meetings held during the Session, to the maintenance of work by the Local Centres, to the progress made by the North Midland Local Centre, which had received official recognition, and of the newly formed Sub-Centre in the Nottingham area. Attention was drawn to the completion of the Fellowship Scheme mentioned in the Report. The President also reviewed briefly the accounts for the past year. The very satisfactory surplus shown was due in part to an inevitable diminution in the number of meetings and corresponding expenditure, but it was also most gratifying in showing the sustained support which the Society had received. In the absence of the Hon. Treasurer, who had been detained by official duties, he read out the official statement of the auditors at the foot of the accounts.

A resolution: "That the Report of the Council for the Session 1939-1940 and the Accounts of the Illuminating Engineering Society for the period from January 1, 1939, to December 31, 1939, be hereby adopted, and a Vote of Thanks be extended to the President, Council, and Officers for their efforts on behalf of the Society during the past Session," was proposed by MR. STEPHEN LACEY and seconded by MR. A. E. ILIFFE.

In moving the resolution MR. LACEY emphasised the importance of the Society and of the work it was doing, and its national value in time to come. Its value to the authorities had been enhanced by its power of combining the resources of all sections of the lighting industry, and by the existence of the common platform which the Society provided. He spoke in high terms of the work of the President, and was glad that he and others associated with the Gas Light and Coke Company had been able to be of good service to the Society during this difficult period.

MR. A. E. ILIFFE, speaking as a representative of the electrical industry, cordially endorsed what had been said by Mr. Lacey in regard to the value of the common platform for gas and electrical interests which the Society afforded. He expressed his appreciation of the excellent work done by the President, of whose wide outlook and ability to take an impartial view he had himself had experience on committees. He supported the resolution with pleasure and congratulated the Officers and Council on their achievements during the past session.

The resolution, having been put to the meeting, was carried with acclamation.

The President then made an announcement in regard to the Followship Scheme, in similar terms to the official notice to be found below.

In conclusion, a resolution: "That this meeting records appreciation of the services of Messrs. Robert J. Ward and Co. as Auditors of the Society and approves their re-election for the next Session," was put to the meeting and declared carried unanimously.

CONDITIONS OF FELLOWSHIP.

The Council of the Illuminating Engineering Society is now prepared to proceed with the Scheme of Fellowship, approved by members at the special meeting on Dec. 5, 1939. An announcement to this effect was made at the annual general meeting on May 7, 1940.

The initial Board of Fellows has been established. This Board has framed rules of procedure to apply from now onwards, and has prepared the necessary form of application. Copies of the form can now be obtained from the honorary secretary by members who desire to apply for Fellowship.

Full information in regard to the conditions of Fellowship, as prescribed in the new by-laws, is given on these forms, and is reproduced on the opposite page. It may be recalled, however, that a Fellow is required to be at least twenty-eight years of age, and to have been a Corporate Member for at least two years, to satisfy certain alternative conditions in regard to technical proficiency and experience, and to give the names of at least three Corporate Members in support of the application.

It is anticipated that the Board will be in a position to announce the first List of Fellows very shortly. It has, however, been agreed that the increased subscription involved (10s. 6d. per annum) shall not commence until Jan. 1, 1941.

CONDITIONS OF FELLOWSHIP

The numbers attached to paragraphs are those of the Clauses in the By-Laws from which these extracts are taken.

Qualifications.

4. The Council may elect as a Fellow any candidate who is at least twenty-eight years of age and who has been a Corporate Member of the Society for at least two years, provided that in exceptional circumstances the Council shall have power to reduce this period.

A candidate for Fellowship shall have held a responsible position requiring proficiency in the technical aspects of illumination for a period of not less than five years, and shall have :—

(a) The Final Grade Certificate in Illuminating Engineering of the City and Guilds of London Institute, or an equivalent qualification approved by the Council ; or

(b) A Science or Engineering Degree of a British University, or equivalent qualification approved by the Council ; or

(c) The Corporate Membership of the Institution of Electrical Engineers or the Institution of Gas Engineers ; or

(d) Achieved an outstanding position in illuminating engineering as a result of wide experience, or a specialised knowledge of some particular branch.

Professional Use of Titles.

9. A Fellow shall be entitled to the exclusive use after his name of the initials "F.I.E.S.," to state that he is a Fellow of the Illuminating Engineering Society, and to adopt the initials "F.I.E.S." in connection with his professional or business activities.

But the use of statements or initials indicating connection with the Society in such a manner shall be confined to Fellows and shall not be practised by members of other grades.

Certificates.

12. Subject to such regulations and on payment of such fees as the Council may from time to time prescribe, the Council may issue to any Fellow or Sustaining Member a certificate indicating the nature of his connection with the Society. Every such certificate shall remain the property of and shall on demand be returned to the Society, and shall contain the statement mentioned in Clause 12 of the Articles of Association.

Admission of Fellows.

17. Applications for Transfer to Fellow shall be made on the appropriate form to the Secretary of the Society, and shall give information to show that the applicant fully complies with the regulations laid down for admission to Fellowship, and shall give the names of three Members of the Society, preferably Fellows, who from personal knowledge of the applicant are prepared to support his application.

The Secretary shall then obtain a written statement from each of the three referees as to their opinion of the suitability of the applicant to be accorded the honour of Fellowship of the Society. When the papers are thus completed, they shall be forwarded in confidence to a Board of Fellows, appointed by the Council, whose names shall not be made public, whose duty it shall be to consider each application individually and make recommendations to the Council. The Secretary of the Society shall inform the applicant of the decision of the Council.

Any candidate whose application has not been approved, may make a further application in due course, or he may request that his case be reconsidered by the Council.

Resignations.

19. Resignation from Fellowship shall not necessarily involve resignation from Corporate Membership unless a notice to this effect is also given.

Subscriptions.

21. The Annual Subscription of Fellows to the Society shall be £2 . 12 . 6.

26. The Annual Subscriptions of Fellows over thirty-five years of age may be compounded by paying 30 guineas if the Fellow is between the ages of 35 and 45, and 25 guineas if over 45 years of age.

A Life Member who has already compounded for his subscription as a Corporate Member may, on becoming a Fellow, compound for his additional subscription by supplementary payment of 5 guineas.

Informal Luncheon

As a substitute for the Annual Dinner, inevitably cancelled for the present year, an informal luncheon was arranged on May 7, the date of the Annual General Meeting. The luncheon took place at St. Ermin's Hotel (Westminster), about one hundred members and guests being present. The luncheon was arranged primarily in order to give members, especially those from the provincial Centres, an opportunity of meeting together and hearing from the President a short survey of events during the Session. The opportunity was, however, taken to invite as guests representatives of some of the departments particularly closely associated with the Society's war-time activities.

After the toast of "The King" had been duly honoured the PRESIDENT, in proposing the toast of "Our Visitors," briefly reviewed the past Session. He explained that this luncheon was regarded as an informal event, without any formal list of toasts and without any attempt to secure the presence of representatives of kindred societies. They had, however, felt that an exception should be made in certain instances, notably the authorities with whom the Society had worked in such close co-operation during recent months. He regretted that Dr. R. E. Stradling, of the Ministry of Home Security, had been unavoidably prevented from attending. They were, however, fortunate in the presence of Mr. E. A. Taylor, who was associated with that Department, and of Mr. F. C. Johnson and Colonel W. S. Vince from the Home Office. The Society had also specially invited Mr. Stephen Lacey, as a slight recognition of the help which they had received from the Gas Light and Coke Company, and Mr. C. H. Cox, the chairman of the Electric Lamp Manufacturers' Association, from whose hospitality they had benefited so frequently during the past Session. The President also alluded to the presence of Sir Duncan Wilson (Home Office Factory Department), whose name—though he was a Past President of the Society and "one of us"—he proposed to couple with the toast, since Sir Duncan was the Chairman of the Departmental Committee on Lighting in Factories and Workshops.

The President then reviewed progress during the Session and particularly the important investigations in which so many members of the Society had shared. He also thanked all members for the support which the Council and he had received in maintaining the organisation and activities of the Society. He referred to the introduction of the scheme of "Fellowship" in the Society, regarding which he would be making an announcement at the Annual General Meeting later in the day, as a particularly important development. In conclusion, he alluded to the very satisfactory representation of the Local Centres, who were also the guests of the Society on this occasion, and were to go into conference with members of Council during the afternoon.

Mr. F. C. JOHNSON (Home Office) and Mr. E. A. T. TAYLOR (Ministry of Home Security), in responding, referred in some detail to the investigations in connection with A.R.P. lighting, and testified to the great value of the efforts of the Society and the prompt response of its members in finding solutions for the various problems referred to them. Sir Duncan Wilson, whose period of service as Chief Inspector of Factories had coincided with the introduction of requirements of adequate and suitable lighting into the Factory Act, and who was chairman of the Departmental Committee on Lighting in Factories and Workshops, also responded. He expressed his appreciation of the help of members of the Society who were serving on this Committee. He pointed out that, in the present circumstances, when the "black-out" brought with it special problems, there was more need than ever for attention to industrial lighting.

Mr. J. W. HOWELL (chairman of the North Midland Local Centre), in returning thanks on behalf of the Local Centres, referred to the substantial recent growth in membership in the provinces and to the progress made by Local Centres, whose representatives much appreciated this opportunity of meeting in London and discussing problems of common interest.

Other representatives of Local Centres present included Mr. C. S. Caunt (hon. sec. Nottingham Sub Centre), Mr. M. W. Hime (hon. sec. Glasgow Local Centre), Mr. T. C. Holdsworth (hon. sec. North Midland Local Centre), Mr. Howard Long (Midland Local Centre), Mr. A. H. Owen (North-Western Local Centre), Mr. James Taylor (North-Western Local Centre), and Mr. F. Walker (chairman Nottingham Sub-Centre).

At the afternoon conference there was a most helpful interchange of views on many topics affecting the future of Local Centres, and good progress was made towards determining programmes and activities in the immediate future.

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THE PHOTOMETRIC PROPERTIES OF SOME LUMINESCENT MATERIALS

By W. E. HARPER, B.Sc., Ph.D., MARGARET B. ROBINSON and J. N. BOWTELL, B.Sc.

(Communication from the Staff of the Research Laboratories of The General Electric Company, Limited, Wembley, England.)

(Paper read on Tuesday, April 9th, 1940.)

SUMMARY.

Photometric data of some luminescent paints and lacquers are given which enable these materials to be treated as items of illuminating engineering equipment.

Factors which affect the brightness of a luminescent material are shown to include the type of material, its weight per unit area, the nature of the backing surface, the type and intensity of the exciting radiation and the temperature of the material. The effect of these factors is described and the general effect of deterioration in luminescence with life investigated.

The phenomenon of phosphorescence has also been investigated for certain materials.

A method is given by which luminescent effects may be calculated from a knowledge of visual data of a similar installation.

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APPENDIX.

Examples of the Practical Method of Planning a Luminescent Installation.

1. Introduction.

A considerable amount of research has been carried out on the performance of luminescent materials when applied, for instance, to discharge lamps and cathode ray tubes(1), and also on their fundamental chemical and physical properties(2). Little has, however, been published on those photometric properties of materials in the form of paints, lacquers, and dyes which are of particular interest to the illuminating engineer. With the increasing use of luminescent materials for decoration, display, and sign work, data are required to enable the engineer to decide the number of U.V.* sources and the type of reflecting equipment required to produce desired effects of colour and brightness with given materials. Knowledge is also required of the influence of concentration of the luminescent material on both the brightness when irradiated and the phosphorescence. The latter effect is of special interest in applications where the source of radiation may be extinguished and reliance is placed on the continued emission of light by the phosphor.

Although the terms "fluorescence," "phosphorescence," and "luminescence" have not precise definitions, it is generally accepted that the first term refers to the emission of light while the material is being irradiated. The term "phosphorescence" refers to the continued emission of light after irradiation has ceased. "Luminescence" is a general term covering both phenomena.

The luminescent materials to be dealt with are those excited by long wave U.V. emitted by such sources as H.P.M.V. discharge lamps in nickel oxide ("black" glass) bulbs. The materials considered are those used in the form of paints, lacquers, and dyes. The photometric properties of powders when used in discharge lamps are not included.

Much of the information given in the paper applies to luminescent materials of one manufacture. In practice there will be differences in performance between various makes and variations in the exciting power of sources of a given type. The purpose of the data given is to provide the illuminating engineer

* U.V. will be used throughout the paper as an abbreviation for ultra-violet.

with a general guide so that luminescent materials may take their place as part of the everyday equipment of illuminating engineering.

2. Types of Luminescent Material.

The luminescent materials which are in general use at the present time for producing luminescent lighting effects may be conveniently classified in three groups:—

Class A—Zinc and zinc-cadmium sulphide phosphors.

Class B—Alkaline-earth sulphide phosphors.

Class C—Fluorescent organic materials.

The materials in these three classes differ from one another in both their nature and uses. They are all excited by long wave U.V. energy so that convenient, safe sources are suitable for their excitation.

Class A—Zinc and Zinc-Cadmium Sulphide Phosphors.

Luminescent materials of this class are produced as fine crystalline powders and require to be mixed with a suitable vehicle to form a paint. They provide a wide colour range and a high luminescent brightness and are particularly applicable to decorative and display purposes. Where a phosphorescent effect of about one hour's duration is required, certain members of this class are suitable.

When correctly applied in paint form they have a good durability under all normal conditions of both interior and exterior use. They are, however, relatively costly to produce and are not very suitable for applying to fabrics.

Class B—Alkaline-earth Sulphide Phosphors.

When a long afterglow, maintaining a useful brightness for about twelve hours, is required, the alkaline-earth sulphide phosphors are particularly applicable.

These are similar to Class A materials in their general form and methods of use. Paints incorporating Class B materials tend to be less durable than those of Class A, particularly under outdoor conditions.

Class C—Fluorescent Organic Materials.

Many organic compounds can be prepared as fluorescent lacquers or dyes, and some of them are useful to the illuminating engineer for display and decorative effects.

In general, organic materials have a lower fluorescent brightness than sulphide phosphors giving the same colour. They tend to deteriorate more rapidly in the presence of light and moisture, but are, however, relatively cheap and can be obtained in a fairly wide range of colours.

Examination of many fabrics dyed for normal purposes has shown that very few exhibit fluorescence having a brightness at all comparable with specially prepared materials. In view of the increasing use of fluorescent effects, difficulties met with in dyeing fabrics with highly fluorescent dyes are now receiving some attention.

3. Methods of Application of Luminescent Materials.

The materials are usually prepared as powders, but on account of the rapid deterioration with loss of luminescent brightness of many in the presence of light and moisture, it is generally necessary to incorporate them in appropriate media for practical use.

They can be conveniently made into paints or lacquers, and some have been successfully embodied in solid media such as vitreous enamels and synthetic resins.

Some of the organic materials are also suitable for dyeing fabrics.

Class A—Zinc and Zinc-Cadmium Sulphide Phosphors.

In the process of manufacture the phosphor assumes a specific crystalline powder form, and it is important that the structure should be preserved, as damage to the individual crystals (e.g., by grinding) leads to a diminution in the luminescent brightness.

When the powder is incorporated in a vehicle to form a paint, it is essential that the vehicle used is one specially intended for this purpose. In addition to good brushing and adhesive characteristics, it must be transparent to both visible light and long wave U.V., non-acid, and resistant to moisture.

Where it is intended to spray the paint, a suitable thinner should be added.

In order to obtain the maximum luminescent brightness, the surface to which the paint is applied should be highly reflecting. Where this is achieved by white painting, only leadless paints should be used as the presence of lead causes deterioration in the luminescent properties of the phosphor. When a very uniform brightness over the surface is required, it is advisable to apply the luminescent paint in at least two coats.

If the conditions of service are likely to be severe, e.g., outdoors, an overcoat of a special clear medium should also be applied in order to reduce ageing, and

the consequent loss of luminescence. In some cases, this medium is the vehicle used in preparing the paint.

These binding and protective media are usually proprietary materials and the results which follow apply to only one representative make.

Suitable zinc sulphide phosphors have been incorporated in vitreous enamel and solid synthetic resins with good results. These provide mechanically strong forms of the phosphors. Under outdoor conditions, the durability of the enamels is comparable to that of the best paints using the same luminescent material.

Class B—Alkaline-earth Sulphide Phosphors.

Owing to the tendency of alkaline-earth sulphides to hydrolyse with the evolution of hydrogen sulphide, it is necessary to use a vehicle which is especially resistant to moisture when making these phosphors into paints. In general, a vehicle suitable for Class A phosphors is not suitable for those of Class B and vice versa.

Furthermore, to obtain good durability of the paints under outdoor conditions, it is generally desirable to apply one or more sealing coats of the clear medium between the backing and the luminescent paint in addition to overcoats.

When it is required to spray paints of this class, the proportions of powder and medium are modified, and a suitable thinner added.

Samples of solid synthetic resins embodying these phosphors have been prepared, but it has been found difficult to incorporate them in vitreous enamel.

Class C—Fluorescent Organic Materials.

Many organic materials exhibit fluorescence, although in some cases it is only developed when the material is in solution. For a given material and medium there is a critical concentration of the solution for maximum fluorescent brightness.

In many cases, the organic materials are supplied in a suitable liquid medium for brushing or spraying. Alternatively, suitable fabrics may be rendered luminescent by normal dyeing technique. Special care must be taken if a useful degree of permanence coupled with the best luminescent brightness is to be obtained by dyeing.

Some fluorescent organic materials have been successfully incorporated in celluloid and other solid media.

4. Sources of U.V. for Excitation of Luminescent Materials.

Luminescent materials are excited by the absorption of radiation between certain wavelength limits. Within these limits, the absorption is selective, i.e., some wavelengths are absorbed more than others, and there is usually a well defined maximum in the absorption curve, at which wavelength the incident energy is most efficiently converted into visible light.

The most efficient excitation will be achieved by a source which emits all its radiation in a single line whose wavelength coincides with that of the peak value of the absorption curve. This is never fulfilled in practice, but the 3650 Å triplet emitted by the H.P.M.V. lamp lies sufficiently near to the peak of the absorption curves of zinc sulphide phosphors and organic fluorescent materials to make this lamp a very efficient means for their excitation.

Where a low U.V. output is required, tungsten filament lamps and low-wattage argon-filled negative glow lamps provide convenient sources.

In order that the fluorescent effects shall not be swamped by visible light from the lamps, a so-called "black" or nickel glass filter is used. This glass transmits a high percentage of long-wave U.V., but absorbs practically all the visible light and any dangerous short wavelength radiation. With certain of the H.P.M.V. lamps the outer bulb is itself made of such a glass, and no other filter is required. Where other types of lamp are used,the black glass filter may take the form of a well-glass surrounding the lamp or a screen covering the mouth of the fitting.

The difference in the spectra of H.P.M.V. and tungsten filament lamps necessitates the use of black glasses of different transmission if the maximum U.V. output is to be obtained from each source.

The amount of U.V. transmitted by these black glasses depends on their composition and thickness. Controlling factors are the limiting amount of visible light which can be tolerated and the elimination of the dangerous short-wavelength U.V.

The visible light emitted by the low-wattage argon lamps is so small that a black glass filter is not usually necessary.

The B.S. Specification for luminescent materials (BS/ARP 18) requires the use of a U.V. source which is readily and consistently reproducible. A 500-watt Class A1 type projector lamp, having a specified candle-power and colour temperature, was adopted in conjunction with a Wratten 18A filter.

This filter is of a similar nature to the nickel glass filters, but is specially made and calibrated to give a definite transmission curve in the U.V. spectrum.

The relative outputs of these different sources, in terms of the luminescent effect produced by them, will be a function of their spectral distributions relative to the excitation curve of the particular luminescent material used.

Table 1 gives the relative U.V. outputs for a series of sources in terms of the luminescent brightness of the three classes of materials. For each class of material the brightness with the B.S.S. source is taken as unity.

The figures represent mean values obtained for a number of sources of each type when new, and are expressed in terms of the U.V. output in a given direction of the standard B.S.S. source. The specimen and lamp were mounted vertically. The horizontal line through the light centre of the lamp passed perpendicularly through the centre of the specimen. The argon lamp was mounted horizontally.

Unavoidable variations in the energy output of lamps and in the density of the black glass filters will cause the figures given in the table to vary in practice, but the results given are typical and will serve for illumination calculations. During the life of the lamp the U.V. output will fall, usually to a somewhat greater extent than that of the visible radiation from the unfiltered source.

The relative U.V. outputs of 40-watt and 80-watt H.P.M.V. black lamps compared with the output of the 125-watt H.P.M.V. black lamp are approximately proportional to their respective wattages.

Where tungsten filament lamps are used and the length of their life is not important, a considerable increase in their U.V. output may be obtained by over-running them. Fig. 1 gives a typical relationship between lamp volts and U.V. output measured in terms of the brightness of a zinc sulphide phosphor having a green luminescence. The corresponding curve relating lumens with volts shows that for a given voltage rise the increase in U.V. output is considerably greater than the increase in light output.

TABLE 1.

Relative Performance of Various Sources of U.V. in Producing Luminescence in Materials of Classes A, B and C.

Source	Relative Brightness of Class A Luminescent Materials	Relative Brightness of Class B Luminescent Materials	Relative Brightness of Class C Luminescent Materials
1. 500-watt Class A1 Type Tungsten Projector Lamp and Wratten 18A Filter (BS/ARP 18 Standard Source).	1.0	1.0	1.0
2. 125-watt H.P.M.V. Black Lamp.	15.0	11.0	19.0
3. 250-watt H.P.M.V. Lamp + Black Glass Filter.	11.0	9.0	15.0
4. 230-volt, 150-watt Tungsten G.S. Lamp + Black Glass Filter.	0.20	0.20	0.30
5. 5-watt Argon-Lamp (No Filter).	0.05	0.04	0.05

(N.B.—The above figures are ratios, and no inter-comparison between columns should be made.)

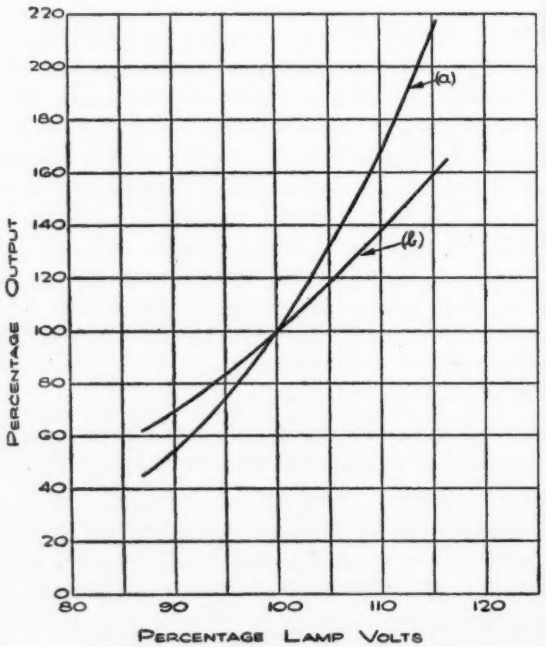

Fig. 1. Relation between lamp volts and
(a) U.V. output,
(b) Lumen output,
for 230 volt 150 watt G.S. tungsten lamp.

5. Brightness of Luminescent Materials.

The brightness of a luminescent material is a function of the coating density or concentration of the material, i.e. its weight per unit area, the reflection from any surface on to which it is coated, the inten-

sity of irradiation, and the temperature of the material. Any deterioration of the luminescent properties with life will also affect the brightness.

(i) Effect of Concentration of the Luminescent Material on Brightness.

With phosphors of Classes A and B, when the paint is sprayed on, there is a rapid increase in brightness with increase in phosphor concentration at first, but this becomes progressively less for equivalent increases in weight as shown in Fig. 2. This figure

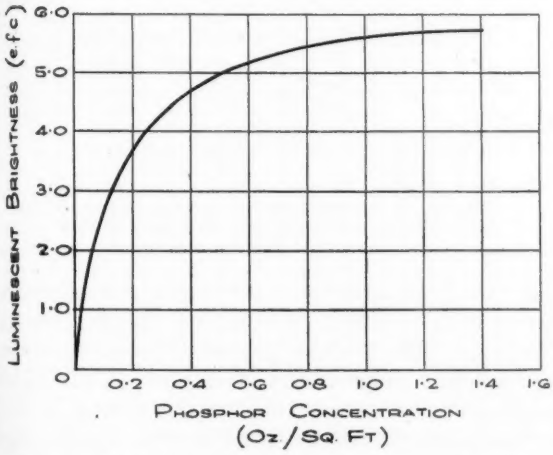

Fig. 2. Relation between luminescent brightness and phosphor concentration for ZnS.Cu. paint on bristol board when irradiated by 125 watt H.P.M.V. black lamp at 3 feet.

gives the relationship between the weight of phosphor per unit surface area and the brightness for a zinc sulphide paint having a green luminescence, when applied to bristol board and irradiated by a 125-watt H.P.M.V. black lamp under constant conditions.

From this curve it may be deduced that phosphor concentrations of 0.5—0.8 oz./sq. ft. represent economic "optimum" weights, the actual value selected being an arbitrary compromise between brightness and cost.

The curve may be taken as typical for this class of materials. Similar tests on other zinc and zinc-cadmium sulphide phosphors gave curves having substantially the same form.

For certain sign and decorative effects, it is required to spray the paint on to a glass surface and irradiate it from the back. The relationship between the phosphor concentration and the "transmitted" luminescent brightness is shown in Fig. 3, which gives the curve for a zinc sulphide phosphor having a blue luminescence. There is here a clearly defined "optimum" value of phosphor concentration, beyond which any increase leads to a progressive decrease in brightness due to increasing absorption. It may, however, be necessary to work at concentrations rather greater than the optimum value on account of the difficulty of applying uniform coatings of low weight.

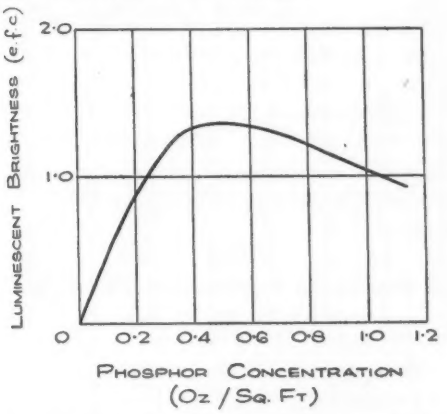

Fig 3. Relation between transmitted luminescent brightness and phosphor concentration for ZnS.Ag paint on glass, when irradiated by 125 watt H.P.M.V. black lamp at 3 feet.

In the case of some fluorescent organic lacquers applied to a bristol board backing, an analogous effect has not been observed, increase in the number of coats of proprietary lacquers resulting in a deepening of the fluorescent colour with no apparent increase in fluorescent brightness. It will therefore frequently be found that one coat of such materials applied to a reasonable thickness gives the optimum brightness.

(ii) Effect of Backing on Brightness.

When the maximum brightness is desired from the luminescent surface on which the exciting radiation falls, light which is transmitted by the paint can be utilised to increase the brightness by the provision of a reflecting backing. The degree of increase due to the backing is naturally dependent on the thickness of the material, decreasing as the thickness increases. At the concentrations generally recommended for practical use, the increase in brightness is nevertheless sufficient to make it advisable to use a highly reflecting backing wherever possible.

Table 2 shows the percentage increase in the brightness of a powder layer painted to a concentration of 0.5 oz./sq. ft. when irradiated and backed with various surfaces. The paint was coated on to a $\frac{3}{64}$ in. clear glass slide to the back of which the reflecting

surfaces were applied. A zinc sulphide phosphor with a green luminescence was used for these experiments, but the results may be taken as fairly typical for other phosphors of the same type. While Table 2 gives the relative effects of using different backings, greater actual increases in brightness will be obtained when the paint is directly in contact with the reflecting surface.

TABLE 2.

Effect of Backing on Brightness of Zinc Sulphide Paint (0.5 oz. per sq. ft.).

Backing	Percentage increase over brightness of unbacked paint
1. Silvered Glass Mirror	20
2. Stainless Steel	10
3. Pot Opal	25
4. Bristol Board	25
5. Leadless White Paint	25

It is of interest to record that a phosphor layer to a concentration of only 0.5 oz./sq. ft. coated on bristol board gave an irradiated brightness only 25 per cent. less than that of a mass of powder sufficiently thick to be just opaque and having a concentration of 50 oz./sq. ft.

(iii) Effect of Intensity of Irradiation on Brightness.

The brightness of any given luminescent material when irradiated is naturally dependent on both the nature and the intensity of the exciting radiation.

Investigations were made to determine whether or not the fluorescent brightness is inversely proportional to the square of the distance of the exciting source as with visual illumination. The brightnesses of selected materials at a series of distances from the U.V. source were measured and the relation between brightness and $\frac{1}{(\text{distance})^2}$ plotted for each material. The linearity of these relationships, as shown in Fig. 4, demonstrates that the brightness of any luminescent material is proportional to the irradiation falling on it within the limits of the experiments.

Luminescent brightnesses have been measured in all cases by the normal visual photometric method using appropriate colour filters.

At low brightnesses (below 0.1 e.f.c.) the sensitivity curve of the eye shifts towards the blue end of the spectrum. Consequently, at these low levels, surfaces having, for instance, red and blue luminescence, may be equally bright as measured photometrically. When viewed by the eye, however, the blue surface will probably appear considerably brighter. This phenomenon (known as the Purkinje effect) is not peculiar to luminescence, but in view of the low brightnesses which frequently occur in luminescent work, particularly in phosphorescent effects, the illuminating engineer should allow for this when designing installations.

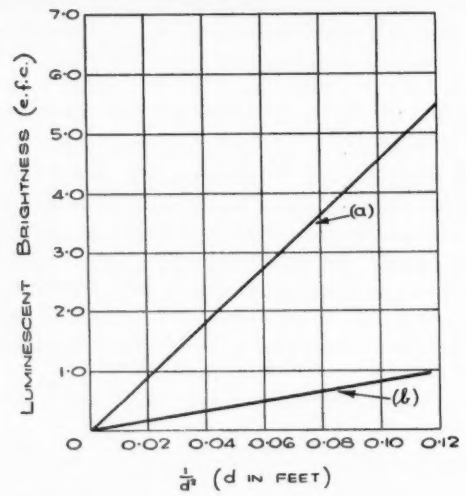

Fig 4. Relation between luminescent brightness and intensity of irradiation for (a) ZnS.Cu. phosphor, (b) alkaline earth sulphide phosphor when irradiated by 125 watt H.P.M.V. black lamp.

The magnitude of the effect increases as the brightness decreases. Data enabling a suitable allowance to be made have been given by Walsh[3].

(iv) Effect of Temperature on Brightness.

The brightness of phosphors of Class A and Class B is not greatly affected by normal variations in room temperature. Where, however, the powder is used in close proximity to the lamp or to some other source of heat, the resulting rise in temperature may be sufficient to affect materially the luminescent brightness.

The variation in brightness with rise in temperature from 0°C. has been studied for Class A phosphors[4], and the curve of Fig. 5 gives the relationship for a zinc-cadmium sulphide having an orange luminescence. At approximately 100°C. the brightness begins to fall rapidly as the temperature is increased, until at 300°C. the luminescence is almost extinguished.

The rate of decrease in brightness with temperature

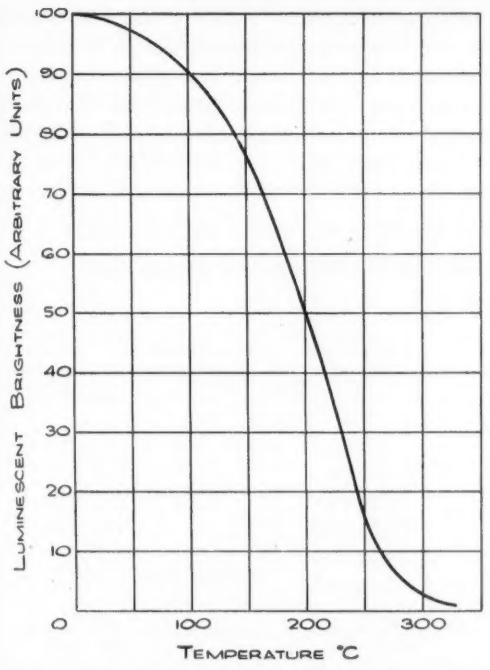

Fig. 5. Relation between luminescent brightness and temperature for Zn.Cd S phosphor when irradiated by 125 watt H.P.M.V. black lamp.

varies widely for different zinc and zinc-cadmium sulphide phosphors.

(v) EFFECT ON BRIGHTNESS OF DETERIORATION WITH LIFE OF LUMINESCENT MATERIALS.

Using known suitable media and present technique of application paints and lacquers embodying the three classes of luminescent substances dealt with vary considerably in durability under similar conditions of service.

Accurate information regarding the effect on luminescence of depreciation with life is difficult to obtain on account of the large number of variable factors involved. Such factors include location, weather conditions, surface to which the paint is applied, protective coats and background paint.

Table 3 indicates the results of a series of tests on luminescent paints of Class A and Class B, using specially developed protective media. If media not specially developed for this protective purpose are used a much more rapid deterioration will occur.

The analogous effect for Class C organic materials has not been investigated under controlled conditions, but general observation indicates that in the majority of cases the deterioration in fluorescent brightness is considerably more marked than for the inorganic phosphors.

TABLE 3.

Effect of Deterioration with Life on Brightness of Luminescent Materials.

Phosphor	Undercoat Backing	Protective Coats	Exposure Details	Percentage Decrease in Brightness
1. Zinc Sulphide (Green luminescence)	White Paint on Wood	1 overcoat	Exposed for five Winter months in unprotected position outdoors	20
2. Zinc-cadmium Sulphide (Orange luminescence)	White Paint on Wood	1 overcoat	Exposed for five Winter months in unprotected position outdoors	20
3. Alkaline-earth Sulphide	White Paint on Wood	2 sealing coats; 3 overcoats	Exposed for three Winter weeks in unprotected position outdoors	20
4. Alkaline-earth Sulphide. (Note: Brightness greater and stability lower than 3)	White Paint on Wood	2 sealing coats; 3 overcoats	Exposed for four Winter months in unprotected position outdoors	50

(vi) BRIGHTNESS OF LUMINESCENT MATERIALS UNDER GIVEN CONDITIONS.

In order to calculate the brightness of a luminescent material under any known conditions, data giving the brightness under some standard conditions are required.

As a convenient arbitrary standard for the preparation of these data, the specimens were mounted 3 ft. from a 125-watt H.P.M.V. black lamp. Both specimen and lamp were mounted vertically, the horizontal line through the light centre of the lamp passing perpendicularly through the centre of the specimen. The results are given in Table 4.

Where painted specimens were used, the paint or lacquer was freshly applied to a bristol board backing, and in the case of Class A and Class B materials the phosphor concentration was 0.5 oz./sq. ft. All measurements were made at temperatures of 15-20° C. by a visual photometer using suitable colour filters.

sity for measurements of this nature and enables existing luminous polar curve data to be used.

If a normal lighting lamp in a given reflector produces a certain visual illumination and if a factor is known for any given luminescent material by which this illumination must be multiplied to give the brightness of the material when a U.V. filter surrounds the lamp, then the brightness distribution on the phosphor can be calculated by the methods used in ordinary illumination calculations.

TABLE 4.
Brightness of Luminescent Materials coated on to bristol board and irradiated by 125-watt H.P.M.V. Black Lamp at 3 ft.

Class of Material	Composition of Material	Form	Luminescent Colour	Concentration of Material	Brightness in e.f.c.
Class A ...	Zinc-Cadmium Sulphide	Paint	Red	0.5 oz./sq.ft.	0.5
	,, ,, ,,	,,	Orange		2.1
	,, ,, ,,	,,	Yellow		4.5
	Zinc Sulphide	,,	Green		5.0
	,, ,,	,,	Deep Blue		0.8
	,, ,,	,,	Light Blue		2.0
	,, ,,	Vitreous Enamel	Green		4.5
Class B ...	Strontium Sulphide (Alkaline-earth)	Paint	Sea Green	0.5 oz./sq. ft.	0.9
Class C ...	Organic materials	Lacquer	Orange-Red	One coat	0.4
	,, ,,	,,	Yellow		2.0
	,, ,,	,,	Lemon		1.9
	,, ,,	,,	Green		1.8
	,, ,,	,,	Blue		0.7

By combining these values with those of Table 1 and applying the inverse square law, the brightness of any of the given materials at any distance from the sources described can be determined, e.g., brightness of a red zinc-cadmium sulphide phosphor at 9 ft. from a 250-watt H.P.M.V. lamp and black glass filter

$$= 0.5 \times \frac{11}{15} \times \frac{(3)^2}{(9)^2}$$

$$= 0.04 \text{ e.f.c.}$$

6. Practical Method of Planning a Luminescent Installation.

In planning a luminescent installation it is desirable to be able to calculate the brightness obtained when given luminescent materials are irradiated by lamps in equipment for controlling the U.V. radiation.

This information could be given in the form of polar curves for equipment providing U.V. radiation, in terms of the brightness produced at unit distance on a given powder or paint of known concentration. The following approach, however, avoids the neces-

Table 5 gives values of the conversion factor:—

$$\frac{\text{(Luminescent Brightness in e.f.c.)}}{\text{(Visual Illumination in f.c.)}}$$

for a number of sources and for the luminescent materials listed in Table 4, when coated on to bristol board. The concentration of materials of Classes A and B was 0.5 oz./sq. ft.

This method of calculation depends upon a knowledge of the shape of light distribution curve produced by the fitting with a source having the same dimensions as the source of U.V. radiation and assumes the reflection and transmission factors of normal redirective lighting equipment to be the same for long-wave U.V. radiation and visible light. Tests have shown that this latter point is usually true within the accuracy required. Thus if H.P.M.V. black lamps in a given fitting are to be used for excitation, the polar curve of the fitting is required when equipped with the corresponding H.P.M.V.

lamp in a clear glass bulb. If tungsten filament lamps and separate black glass filters are to be used, the light distribution required is that with the similar tungsten filament lamp unfiltered. An example of the method of calculation is given in the Appendix.

In the case of the long afterglow powders of Classes A and B, the rate of growth of brightness with time of excitation is sufficiently slow to be measured visually. Fig. 6 gives a typical growth curve for a long afterglow zinc sulphide phosphor, having a green luminescence, the brightness at any given time being expressed as a fraction of the maximum brightness.

TABLE 5.

Factors for the Conversion of Visual Illumination in f.c. into Luminescent Brightness in e.f.c. for Various Sources and Luminescent Materials. Materials coated on to bristol board.

Class of Material	Composition of Material	Luminescent Colour	Concentration of Material	Luminescent B. in e.f.c. / Visual Illumination in f.c. for		
				40w., 80w. and 125w. HPMV Black Lamp (Quartz inner)	250w. and 400w. HPMV Lamp (Glass inner) + Black Glass Filter	General Lighting Service 230v. 200w. Tungsten Lamp* + Black Glass Filter
Class A	Zinc-Cadmium Sulphide	Red	0.5 oz./sq. ft.	0.011	0.006	0.0005
,,	,, ,, ,,	Orange		0.047	0.024	0.003
,,	,, ,, ,,	Yellow		0.100	0.050	0.004
,,	Zinc-Sulphide	Green		0.110	0.054	0.005
,,	,, ,,	Deep Blue		0.018	0.009	0.0006
,,	,, ,,	Light Blue		0.035	0.020	0.003
Class B	Alkaline-earth Sulphide	Sea-Green	0.5 oz./sq. ft.	0.020	0.011	0.001
Class C	Organic Material	Orange-Red	One Coat	0.009	0.004	0.0005
,,	,, ,,	Yellow		0.044	0.024	0.001
,,	,, ,,	Lemon		0.042	0.022	0.002
,,	,, ,,	Green		0.041	0.022	0.0015
,,	,, ,,	Blue		0.016	0.007	0.0007

* Efficiency approx. 14 lumens per watt.

7. Growth of Luminescent Brightness.

(i) GENERAL.

When phosphors are irradiated they do not reach maximum brightness immediately radiation falls upon them. The process is a progressive one, the rate of excitation and the resultant growth in brightness being determined by several factors, including the nature of the phosphor and the intensity of irradiation.

The process appears to be closely associated with the corresponding phenomenon of phosphorescence. Phosphors which have only a short afterglow rapidly reach maximum brightness; those having a long afterglow require to be irradiated for a longer time before they are fully excited.

The period of growth to the maximum brightness varies from small fractions of a second for fluorescent materials to several minutes for the alkaline-earth sulphides when irradiated by a 125-watt H.P.M.V. black lamp 6 ft away.

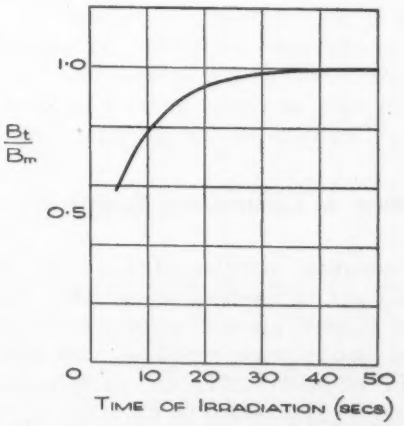

Fig. 6. Curve of growth of luminescent brightness of ZnS.Cu phosphor when irradiated by 125 watt H.P.M.V. black lamp at 6 feet.

In view of the similarity in the mechanism of luminescence of the Class B phosphors, the form of the growth curve of luminescent brightness is the same as that of the Class A type, but the rate of growth is slower.

The luminescent organic materials of Class C display no phosphorescence, i.e., have a decay time of the order of atomic reactions, in effect an instantaneous response to excitation.

(ii) Effect of Intensity of Irradiation on Rate of Growth of Luminescent Brightness.

If the intensity of irradiation of a phosphor is increased, the rate of rise to maximum brightness is increased, as is the actual value of this maximum.

Fig. 7 shows the curves of growth of brightness for a long afterglow zinc sulphide phosphor, having

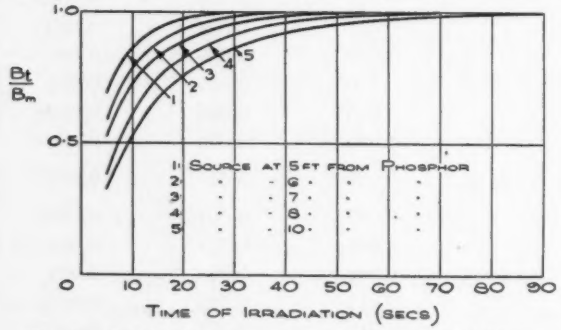

Fig. 7. Relation between growth of luminescent brightness and intensity of irradiation] for ZnS.Cu phosphor when irradiated by 125 watt H.P.M.V. black lamp.

green luminescence, when excited by U.V. radiation of different intensities.

From these curves it can be deduced that the time taken to reach the maximum brightness is inversely proportional to the intensity of irradiation.

Where long afterglow phosphors are excited by tungsten sources having a relatively low U.V. output, it is generally necessary to allow an excitation time of several minutes for the phosphor to be fully excited.

8. Decay of Luminescent Brightness.

(i) General.

By the common understanding of the terms fluorescence and phosphorescence the organic materials of Class C are not phosphorescent, while the zinc and zinc-cadmium sulphide and alkaline-earth sulphide phosphors all exhibit phosphorescence to some degree. The period of duration of visible phosphorescence varies from a few seconds for some of the zinc and zinc-cadmium sulphide phosphors to two or three days for those of Class B.

Although the duration of phosphorescence varies widely, the fundamental process in the cases under discussion is similar and the curves of decay of brightness shown in Fig. 8 are typical of zinc sulphide and alkaline-earth sulphide phosphors.

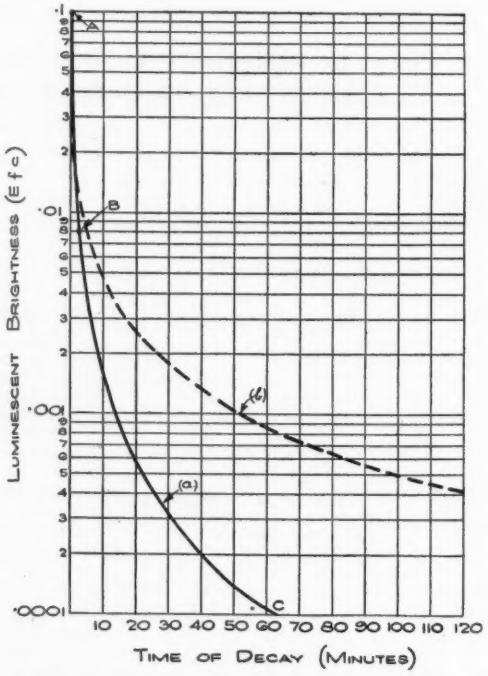

Fig. 8. Curves of decay of luminescent brightness of (a) ZnS. Cu phosphor (b) alkaline-earth sulphide phosphor after irradiation by source specified in BS/ARP 18.

In the case of the zinc-sulphide phosphor, when irradiation ceases the brightness falls rapidly giving the initial portion AB of the curve. Subsequently, the rate of decay becomes less, producing the portion BC of the curve. This sub-division of the curve is entirely arbitrary and has been adopted only for convenience of description.

Curves of decay of brightness having this form may be expressed satisfactorily by the formula:—

$$B_t = \frac{B_o}{(1 + \alpha t)^2} \quad (5)$$

where

B_o = Brightness of phosphor at time O;
B_t = " " " t secs. after irradiation has ceased.
α = Constant depending on both the phosphor and the absolute temperature.

The corresponding curve of the alkaline-earth

sulphide phosphor has generally a lower initial brightness than that of the zinc sulphide, but a more pronounced phosphorescence, the two curves crossing after a few minutes. Under conditions of good dark-adaptation zinc-sulphide phosphors having similar characteristics to the example given, will provide a useful indication for about one hour after irradiation has ceased. The corresponding time for the alkaline-earth sulphides is approximately seven hours, both phosphors having a brightness of 0.0001 e.f.c. after these time intervals and an initial brightness greater than that given by the "saturation excitation." (See following section.)

(ii) Effect of Intensity of Irradiation on Rate of Decay of Luminescent Brightness.

As the brightness of any given phosphor when irradiated increases proportionally to the exciting radiation up to very high values, an increase in excitation leads to a corresponding increase in the portion AB of the curve of decay of brightness. A similar effect is not observed in the phosphorescence, however, beyond a certain upper limiting value of the excitation. If a phosphor is excited to a level higher than this limit, when excitation ceases, the brightness falls rapidly and after a short interval the curve of decay of brightness becomes coincident with the curve given by the limiting value of excitation. Thus while the brightness when irradiated and the initial portion AB of the curve of any phosphor can be increased almost indefinitely by increasing the excitation, the phosphorescence can only be increased up to a limiting value of excitation, which has been termed the "saturation excitation" of the phosphor.

Fig. 9 shows this effect for a zinc-sulphide phosphor having a concentration of approximately 0.5 oz./sq.ft. Any increase in the intensity of irradiation beyond that necessary to give an initial brightness of 0.75 e.f.c. does not appear to lead to any significant improvement in the phosphorescence.

The value of the saturation excitation depends on both the nature and the concentration of the phosphor. Phosphors with large concentrations have higher values of saturation excitation, and so improvement can be effected in their phosphorescence by increasing the irradiation up to this higher limit. But the concentration required to effect a material

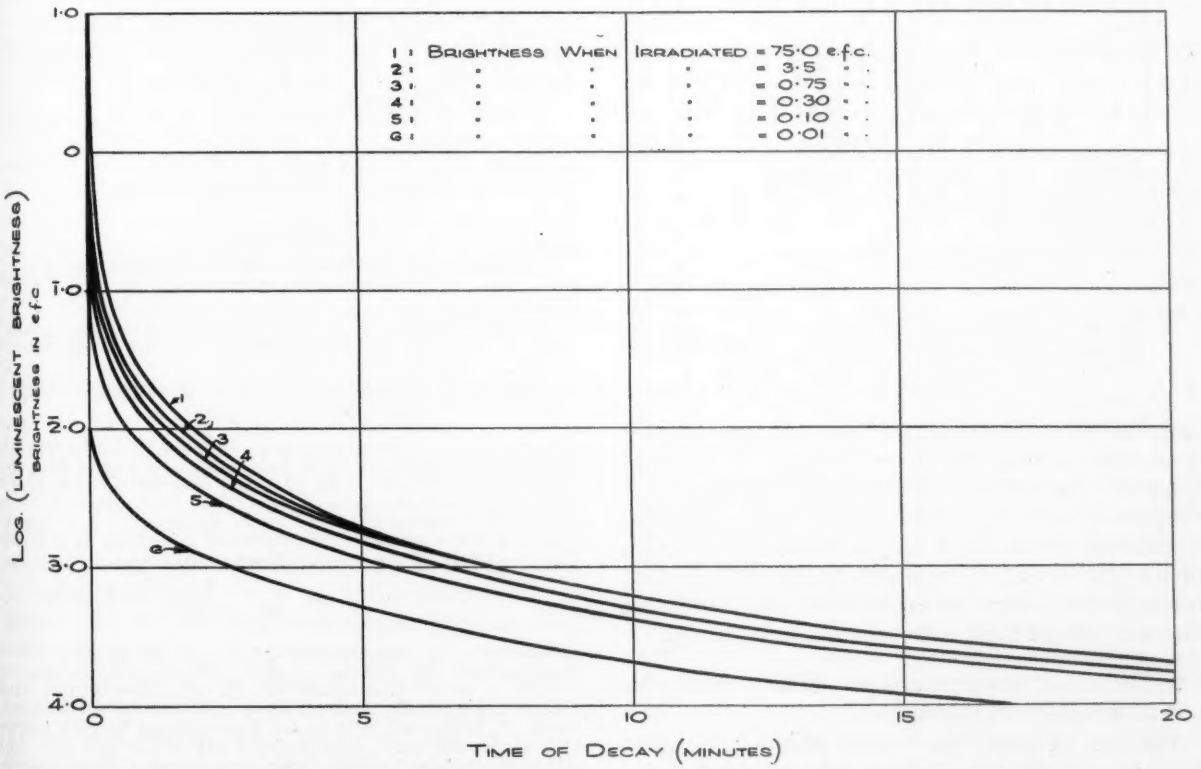

Fig. 9. Relation between intensity of irradiation and rate of decay of luminescent brightness for ZnS. Cu phosphor.

improvement beyond that given by normal concentrations is so great as to render the method impracticable.

(iii) Effect of Phosphor Concentration on Rate of Decay of Luminescent Brightness.

The curves of decay of brightness given in Fig. 8 refer to specimens painted to a concentration of approximately 0.5 oz. of powder per sq. ft., which represents an economic value for these phosphors.

Fig. 10 shows the effect of varying the phosphor concentration on the curves of a typical zinc-

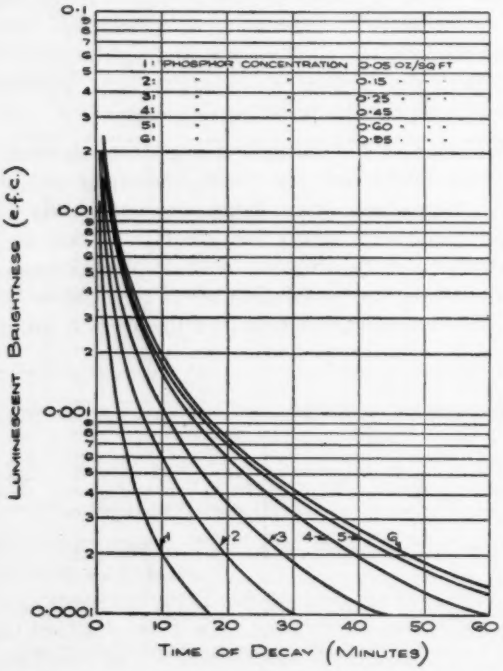

Fig. 10. Relation between phosphor concentration and rate of decay of luminescent brightness for ZnS. Cu phosphor after irradiation by source specified in BS/ARP 18.

sulphide which was irradiated under constant conditions. By plotting the times of decay to the same brightness against the corresponding phosphor concentrations, as in Fig. 11, the form of this relationship is obtained. From this it may be deduced that values of 0.5—1.0 oz./sq. ft. represent economic phosphor concentration where the phosphorescence is of major interest, though these values are quite arbitrary.

(iv) Effect of Temperature on Rate of Decay of Luminescent Brightness.

The rate at which the stored energy of a given phosphor is radiated as light after excitation has

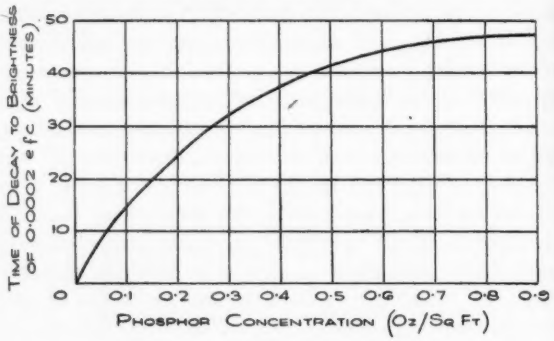

Fig. 11. Relation between phosphor concentration and time of decay to brightness of 0.0002 e.f.c. for ZnS. Cu phosphor after irradiation by source specified in BS/ARP 18.

creased, is affected by the temperature. If the phosphor is warmed, the rate of emission of light is increased, resulting in a greater light output for a shorter time. Cooling has the reverse effect.

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(1) H. G. Jenkins and J. N. Bowtell, Trans. Faraday Society, XXXV., p. 154; L. J. Davies, Trans. Faraday Society, XXXV., p. 171; J. W. Ryde, Trans. I.E.S. (London), Vol. III., No. 8.

(2) J. T. Randall, Trans. Faraday Society, XXXV., p. 2; P. Pringsheim, Trans. Faraday Society, XXXV., p. 28; R. W. Gurney and N. F. Mott, Trans. Faraday Society, XXXV., p. 69; F. Seitz, Trans. Faraday Society, XXXV., p. 74; N. Riehl, Trans. Faraday Society, XXXV., p. 135.

(3) J. W. T. Walsh, "Photometry" (Constable and Co.), p. 65.

(4) J. T. Randall, Journal R.S.A., No. 4398, March, 1937.

(5) F. Seitz, Trans. Faraday Society, XXXV., p. 75.

APPENDIX

Examples of the Practical Method of Planning a Luminescent Installation

Example 1.

It is required to produce a brightness of 5 e.f.c. over a small area of Class A yellow phosphor, 20 ft. from the source of U.V.

Referring to Table 5, it is seen that the conversion factors

$$\frac{\text{Luminescent B in e.f.c.}}{\text{Visual Illumination in f.c.}}$$

for the Class A yellow phosphor are 0.1, 0.05, and 0.004 for the low-wattage HPMV black lamp (40, 80, and 125 watt), the high wattage HPMV lamp (250 and 400 watt), with black glass filter, and the general lighting service tungsten lamp with filter, respectively. The visual illumination it is necessary to provide, so that when the black glass filter is inserted the brightness of the yellow phosphor is 5 e.f.c., will therefore be

$$\frac{5}{0.1}, \frac{5}{0.05} \text{ and } \frac{5}{0.004}$$

respectively, i.e., 50, 100, and 1,250 ft.c. To produce these illuminations at a distance of 20 ft. the intensities required are 20^2 times the illumination values, i.e., 20,000, 40,000, and 500,000 candles. Equipment which will provide these intensities of unfiltered light using low-wattage HPMV lamps (40, 80, or 125 watt), high-wattage HPMV lamps (250 and 400 watt), and general lighting service tungsten lamps respectively, will produce the required 5 e.f.c. brightness with the

yellow luminescent material when black glass filters are employed. No depreciation has been allowed for.

EXAMPLE 2.

It is required to produce an average brightness of 3 e.f.c. in a yellow colour, over a ceiling 10 ft. × 12 ft.

A Class A yellow phosphor will probably be the most suitable. The conversion factors are the same as those used in Example 1, as the powder is the same. The visual illumination it is necessary to provide, so that when the black glass filter is inserted the brightness of the yellow phosphor will be 3 e.f.c., is

$$\frac{0.1}{}, \frac{3}{0.05}, \frac{3}{0.004}$$

for the three classes of source, i.e., 30, 60, and 750 ft.c. The area of ceiling is 10 ft. × 12 ft. = 120 sq. ft., and the lumens required are the product of area and illumination, i.e., 3,600, 7,200, and 90,000 lumens for each type of source.

If indirect reflector units are employed which direct 60 per cent. of the lamp radiation on to the ceiling, then the lamp lumens required are

$$\frac{3,600}{0.6}, \frac{7,200}{0.6} \text{ and } \frac{90,000}{0.6}$$

i.e., 6,000, 12,000, and 150,000 lumens for the three types of source. This output will be provided by two 80-watt H.P.M.V. lamps (3,040 lumens each), one 400-watt (16,000 lumens) or two 250-watt H.P.M.V. (8,000 lumens each), when actually the brightness will be higher than required in the ratio of $\frac{16,000}{12,000}$, or about 10,000 watts of tungsten (the efficiency varying from about 12 to 18 lumens per watt as the wattage is increased from 100 watts to 1,000 watts). The above lamps, when fitted with black glass filters and used in appropriate fittings, are capable of producing an average brightness of 3 e.f.c. on the ceiling described. No depreciation has been allowed for.

DISCUSSION

The PRESIDENT expressed appreciation of the action of the General Electric Company in permitting this paper to be presented to the Society, and also thanked the authors for the very clear manner in which the subject had been placed before the meeting. He said he knew something of the amount of work which was necessarily done in carrying out experiments of the nature described, and added that the Society felt greatly indebted to the authors. Although this was not the first time that a lady had spoken from the Illuminating Engineering Society platform—Miss Partridge having given a paper some years ago on neon tube lighting—this was the first occasion in which a lady, collaborating with gentlemen in research laboratories, had taken part in the presentation of a paper, and as a team he thought the present authors were just fine. Finally, the President remarked that some of the members of the Committee which had been at work on the specification referred to in the paper were present, and he hoped they would take part in the discussion.

Dr. C. C. PATERSON said the subject of the paper was of great interest to the illuminating engineer, since the problem of artificial lighting in the streets at the moment was a study of trying to see without any light. Nevertheless, it seemed to him that the experiences which illuminating engineers were now going through were very good for them, as they were bringing into being, in a rather curious way of course, the kind of conditions he himself had been trying to represent about four years ago in the Guthrie Lecture of the Physical Society. He had discussed the situation which illuminating engineers would have been in, had there never been any artificial light. In these circumstances they would long ago have made an intensive study of contrasts, and in that and other ways would have learned to find their way about at night by the light of nature. He had also mentioned in that lecture the study of luminescent materials to assist in carrying on the hours of daylight into the night. It was curious that these things should now have materialised under the force of circumstances, and it was rather interesting and useful, perhaps, to have a breakaway from the continual use of more and more artificial light and to think of how to get along with less and less artificial light and more and more of the other aids which were to be found at hand in nature.

It was, concluded Dr. Paterson, very interesting to see how the inverse square law seemed to hold for all illuminations, in the manner demonstrated by the authors. He supposed it was right that the curve went down to zero with faint illumination. Could the authors give an assurance that it was still then proportional?

Dr. J. W. T. WALSH referred to that bugbear of the photometrist, the Purkinje effect, and suggested that this tended to enter, in a rather disconcerting way, into the measurement of the brightness of the materials which had been demonstrated when the brightness levels were as low as those which had to be thought about so much at the present time. The authors' demonstrations had been at levels to which we were more ordinarily accustomed, but when we came down to levels of 1/100th or 1/1000th equivalent foot-candle the position might be rather different. That was a matter which must be faced up to in a practical way, because the authors had referred to the preparation of a standard specification for these

materials at these low levels of brightness. It was no use putting into a British Standard Specification figures which were unfair to materials of different colours. For instance, in comparing red and blue materials the blue would be handicapped more and more as the brightness was progressively diminished, if measurements were made on a physical basis. It was necessary, therefore, to put into the specification something which would be reasonably consistent with what appeared to be the correct answer to the man in the street. The solution which was proposed, at any rate for the time being, was to reduce, in any given ratio, the brightness of a defined white colour and then to measure the brightness of any other colour by visual comparison with that white. In that way, they were really doing what the man in the street did when he used the material. The authors had mentioned the use of coloured filters for measurement, and it was possible that this might get over the difficulty to a certain extent. Unless the colour filters gave a reasonable energy match with the lights that were being looked at, however, there was danger of being led astray, because even though there was a sensation colour match it did not necessarily mean that the two colours would be treated in exactly the same way. He wanted to draw attention to this difficulty which had to be met because if the specification, when issued, was not quite as plain sailing as had been looked for, he hoped the reason would be understood.

Dr. T. H. HARRISON said that he also had measured the brightness of several fluorescent surfaces at various distances from a black lamp, and had found that for each surface the brightness was proportional to the inverse square of the distance. The range of distances extended from a few centimetres (when the bulb of the black lamp was almost touching the fluorescent surface) to 12 metres. At this 12-metre distance the intensities both of irradiation and of fluorescent brightness were small, and it therefore seemed that for practical purposes this inverse square relation might safely be extrapolated to the zero point. From a practical point of view Dr. Paterson's question regarding the safety of the extrapolation was thus answered positively, but to answer the academic question of whether there are discontinuities at very low intensities of excitation, a lengthy investigation would be needed. So long as the fluorescent colour did not change with the distance of the lamp, one could not expect the Purkinje effect to confuse the results, providing that the comparison source had the same energy distribution and that the brightness values were consequently measured in the familiar units related to the light-adapted eye (such as e.f.c.). If the energy distribution of the fluorescence differed from that of the comparison field, then the Purkinje effect would operate as the irradiation got lower, giving an apparent systematic deviation from the inverse square relation. If the colour of the fluorescence changed with the distance of the black lamp, or if the fluorescent brightnesses of surfaces of different colour were compared, quite large apparent and even real deviations from the inverse square relation might be observed. If, as was now suggested, the brightnesses of all luminescent surfaces were to be matched with those of a white surface, the inverse square relation would not hold. In the case of a blue specimen, when the fluorescent brightness was decreased, the peak of the visibility curve of the eye shifted towards the blue, and this would make the brightness of the material higher than would be expected from the inverse square relation.

Mr. W. J. EDWARDS, referring to the falling off of luminescence with time, and the figure of 20 per cent. with zinc sulphide over a period of five months, asked if that falling off was proportional to the time. For instance, in two and a half months would it be 10 per cent.? Further, was the falling off due to a change in chemical composition of the active material? If it were due to chemical change he would imagine that, as time went on, the fall in luminescence would increase in greater proportion.

Mr. A. G. PENNY asked whether any measurements had been made upon the brightness of "non-fluorescent" materials when subjected to ultra-violet radiation. He referred to the fact that in all the applications of fluorescence one of the primary objects was to obtain adequate contrast between the fluorescent portions of the display and the background, which should, therefore, be designed to be non-fluorescent and to have a brightness as low as possible.

In the case of illuminated devices of the normal type, the greatest degree of contrast that could be obtained was of the order of 20 to 1, as the highest reflection factor of white paint was about 80 per cent. and the lowest reflection factor of black paint at least 4 per cent.

In the case of fluorescent materials, he had made some preliminary experiments which indicated that

by the proper choice of fluorescent powders and by a suitable non-fluorescent background, a contrast ratio of 200 to 1 could be obtained, thus greatly increasing the visibility.

Mr. Penny demonstrated the point by means of two cards, both of which had the same coloured design on a printer's black ink background, one design being made up with normal coloured printer's inks and the other with fluorescent paints of the zinc sulphide type. The ordinary card was then illuminated with tungsten light and the other with ultra-violet radiation, so that the brightest portions of the two designs were of equal brighness. It was then clearly seen that the background of the fluorescent card was much darker than that of the normally prepared card, and very clearly demonstrated the increased visibility produced by the enhanced contrast.

Mr. J. S. PRESTON expressed his interest in the various properties of luminescent materials so clearly set out by the authors, and asked whether it were possible to obtain two phosphorescent surfaces of markedly different colours, say red and blue, and having similar decay curves. If this were so one might use them for demonstrating the Purkinje effect by starting them off at the same apparent brightness (at some relatively high level), and then observing the *apparent* change in relative brightness during the decay period after removal of the activating source.

Mr. J. S. Dow remarked that the Purkinje effect had always been a subject of interest to him, because this was one of the first things he had been asked to explore as a student more than forty years ago. There was at that time an impression that it was a species of optical illusion, and it was not realised how remarkable was its effect when one was dealing with very feeble illuminations. If the illumination was low enough, and if the image fell on a sufficiently large area of the retina, vivid red objects appeared jet black.

Turning to the author's demonstrations, Mr. Dow expressed his interest in the experiment showing that intensity of irradiation had only a limited effect on phosphorescence. He believed that a certain time was necessary for the luminescence to "build up." In this connection he asked if the authors could state the factors determining the "storage power" of phosphorescent media. He noticed that the authors had mentioned twelve hours as about the limiting time for which a useful phosphorescence could be obtained. He had, however, heard rumours that, with materials of exceptional purity, much longer useful periods were possible, and that in underground chambers thus treated it was possible, after one exposure, to read a newspaper for a fortnight afterwards.

Mr. PERCY GOOD, referring to the question of after-glow and the mention of twelve hours by the authors, said the committee responsible for trying to define usefulness adopted a very low level. He believed it was 0.0001 e.f.c. He himself had not experimented on these materials, but he had tried in an elementary way the after-glow effect on quite a number of samples, and had found that provided one was completely dark adapted there was an after-glow effect which could be noticed for possibly twelve hours. If, however, a person was not completely dark adapted the useful effect would not last for anything like twelve hours. Therefore, in defining this sort of material it was essential to define what was meant by useful after-glow, as there would be a substantial difference depending on the purpose for which the after-glow was needed. A value much higher than 0.0001 e.f.c. would often be necessray.

Mr. H. E. BECKETT inquired whether the manufacture of these materials had been put on a scientific basis, as quite obviously the photometric side had. There had always been a great mystery about it and he believed there were considerable variations between mixes and even in a particular mix. Therefore, he would like to be assured that the scientific aspect of production was being fully considered.

Mr. S. J. PATMORE, referring to the use by the authors of coloured filters in some of their experiments, asked if these filters made any difference to the actual readings obtained when used with a photometer which was set for measuring white light. If there was any difference, could the authors give any information as to the percentage.

Mr. R. BREWER mentioned a device which, if not exactly relevant to the paper, was of considerable interest—the use of phosphorescent material to control the production of artificial reverberation in film and broadcasting studios. The device ingeniously made use of the fact that the rate of decay of the phosphorescence was similar to that of sound.

DISCUSSION

Mr. E. W. MURRAY said that a few years ago he was interested in experiments designed to prevent the fading of the plumage of birds exhibited in glass cases. At the outset it was thought that the fading was caused by the direct action of ultra-violet radiation in the artificial lighting. Attempts were made to absorb the ultra-violet, but these prevented the plumage being seen in its proper colouring. It was subsequently found that when these "stuffed birds" were exhibited in some new air-tight cases and the atmosphere inside the cases kept dry the fading had practically ceased. The cause of this fading was found to be due to the combined action of the ultra-violet radiation with the moisture and the chemical impurities in the atmosphere.

Mr. J. N. BOWTELL, who replied to some of the points raised in the discussion, spoke first on the question of the amount of energy stored by phosphors, raised by Mr. Dow, and said that this could be calculated for the initial part of the decay curve. At the tail end of the curve, where the brightness is very low, the total amount of energy stored is small, but this amount may be measured by releasing it in a short "burst." This burst can be brought about by irradiating the phosphor with infra-red radiation of suitable wavelength. Although the total amount of energy stored by some phosphors, such as those of the alkaline-earth type, is quite small, they may continue to emit light for 2-3 weeks. After two or three days, however, the intensity of the emitted light is too low to be perceived visually.

In reply to Mr. Beckett, he said that the production of modern powders was very carefully controlled. The degree of control necessary was, indeed, as high as that in the most rigorously controlled chemical processes. The purity of the constituent materials and the conditions of furnacing are of the greatest importance in this respect. There may, however, be some variation from batch to batch in the finished materials both in colour and brightness. Limits are laid down to control these variations, and batches falling outside the limits are rejected.

Dr. HARPER, continuing the reply, agreed with Dr. Harrison that confirmation of the inverse square law at very low levels of irradiation would be difficult, but that it could be said to hold for the range of brightness which interested the illuminating engineer, bearing in mind the complications introduced by the Purkinje effect. The authors were interested in the proposed solution for measuring brightnesses at low levels described by Dr. Walsh, but thought observers might experience difficulty with photometric measurements in which there are large colour differences.

In reply to Mr. Preston's suggestion for using red and blue phosphorescence to demonstrate the Purkinje effect, it would probably be difficult to find powders having identical rates of decay. Furthermore, it is difficult to produce a material having a deep red phosphorescence of considerable duration. It would probably be easier to use fluorescent dyes free from phosphorescence and to change the brightness by varying the distance of the irradiating source.

Experiments dealing with the depreciation with life of luminescent materials had not been carried on for a sufficient length of time and under sufficiently stringent conditions to enable definite conclusions to be reached. The results obtained so far, however, did not seem to indicate that the rate of depreciation increased with time as suggested by Mr. Edwards; indeed, the reverse was almost certainly the case. It was hoped to continue measurements on this point.

The authors had not measured the brightness of non-fluorescent materials when subjected to ultra-violet radiation, but Mr. Penny's demonstration clearly indicated the enhanced contrast which could be obtained by using fluorescent materials on a non-fluorescent background.

The authors had not come across a non-radio-active powder having a useful phosphorescence lasting for a fortnight, which would be a remarkable achievement. The growth of luminescence mentioned by Mr. Dow was often important and is treated fully in the printed paper.

A controversial point had been raised by Mr. Good when he referred to "useful" afterglow. The authors had adopted the figure of 0.0001 e.f.c., which had been used by the B.S. Committee, as this brightness can clearly be seen after short dark adaptation and is near the lower limit of measurement. It would possibly be of value to give the duration of afterglow to various brightness levels and to correlate the brightness required with the adaptation of the observer, and thus to determine the duration of useful afterglow in any circumstances.

Finally, in reply to Mr. Patmore, measurements in which the photometric balance is made against white light are now in hand, but no comparisons have yet been made between this method and that involving the use of colour filters.

FELLOWSHIP*

First List of Fellows Issued

In response to the announcement made at the annual general meeting on May 7, which also appeared in the last issue of "The Transactions" (May, 1940; p. 54), numerous applications for transfer to the new class of "Fellow" have been made, and are still being received.

In the time available it has been impossible to review all the applications received.

The Board has, however, recommended the election of the following as Fellows of the Society, and their recommendation has been approved by the Council:—

Ackerley, R. O.	Verandah Cottage, 4, Richmond Hill, Richmond, SURREY.
Applebee, L. G.	48, Cambridge Avenue, New Malden, SURREY.
Bennett, M. G.	Chief Engineer's Dept. Headquarters, London Midland and Scottish Railway, The Grove, Watford, HERTS.
Beuttell, A. W.	100, Victoria Street, Westminster, LONDON, S.W.1.
Brown, A. G.	8, Coombe Gardens, West Wimbledon, LONDON, S.W.20.
Buckley, Dr. H.	The National Physical Laboratory, Teddington, MIDDLESEX.
Chandler, D.	14, Calais Gate, Myatt's Park, LONDON, S.E.5.
Colquhoun, J. F.	Corporation Lighting Department, 13-21, Matthew Street, SHEFFIELD 3.
Cunnington, A.	Lighting Engineer's Department, The Southern Railway, Waterloo Station, LONDON, S.E.1.
Dow, J. S.	Mayfield, 48, Shepherds Hill, Highgate, LONDON, N.6.
Edgcumbe, Lt.-Colonel Kenelm	Collindale Works, Hendon, LONDON, N.9.
English, Dr. S.	Holophane, Ltd., Elverton Street, Vincent Square, LONDON, S.W.1.
Evans, Colonel C. H. Silvester	C/o Lloyds Bank, Ltd., 86, High Street, Wimbledon Hill, LONDON, S.W.19.
Good, Percy	The British Standards Institution, 28, Victoria Street, LONDON, S.W.1.
Hampton, Dr. W. M.	Chance Bros. and Co., Ltd., Glass Works, Smethwick, BIRMINGHAM.
Harrison, Lt. Commander Haydn T.	60, Becmead Avenue, Streatham, LONDON, S.W.16.
Howell, J. W.	E.L.M.A. Lighting Service Bureau, Circle House, 29, Lady Lane, LEEDS 2.
Jones, W. J.	25, Rosemary Avenue, Finchley, LONDON, N.3.
Juliusburger, H. H.	37, Arundel Gardens, LONDON, W.11.
Langlands, S. H. B.	1413, Pollokshaw Road, GLASGOW, S.1.
Lingard, H.	12, Northaw Road, Cuffley, HERTS.
Long, Howard	115, Hampton Lane, Solihull, BIRMINGHAM.
MacGregor-Morris, Dr. J. T.	3, Lyndhurst Road, Hampstead, LONDON, N.W.3.
Minchin, L. T.	7, Beverley Road, Barnes, LONDON, S.W.13.
Paterson, Dr. C. C.	The Research Laboratories of the General Electric Co., Ltd., Wembley, MIDDLESEX.
Peirce, M. W.	Bracken, 57, Park Avenue, Ruislip, MIDDLESEX.
Preston, J. S.	159, Burton's Road, Hampton Hill, MIDDLESEX.
Ritchie, T. E.	1, Elm Bank Mansions, The Terrace, Barnes, LONDON, S.W.13.
Sawyer, K. F.	The Gas Light and Coke Company, Watson House, Townmead Road, Fulham, LONDON, S.W.6.
Smith, F. C.	The Gas Light and Coke Company, Watson House, Townmead Road, Fulham, LONDON, S.W.6.
Stevens, W. R.	125, The Fairway, North Wembley, MIDDLESEX.
Stewart, E. J.	Corporation Lighting Department, 20, Trongate, GLASGOW, C.1.
Stroud, E.	"Blue Firs," 43, West Drive, Cheam, SURREY.
Trotter, A. P.	Greystones, Teffont, SALISBURY.
Waldram, J. M.	24, Hill Road, Pinner, MIDDLESEX.
Waldram, P. J.	9, Grays Inn Square, LONDON, W.C.1.
Walsh, Dr. J. W. T.	The National Physical Laboratory, Teddington, MIDDLESEX.
Weston, H. C.	Inverclyde, The Avenue, Orpington, KENT.
Wilson, G. H.	46, Lawns Court, The Avenue, Wembley, MIDDLESEX.

* The attention of those desiring to apply for transfer to the class of Fellow is drawn to the qualifications presented in Clause 4 of the new By-Laws, which is as follows: —

4. The Council may elect as a Fellow any candidate who is at least 28 years of age and who has been a Corporate Member of the Society for at least two years, provided that in exceptional circumstances the Council shall have power to reduce this period.

A candidate for Fellowship shall have held a responsible position requiring proficiency in the technical aspects of illumination for a period of not less than five years, and shall have:—

(a) The Final Grade Certificate in Illuminating Engineering of the City and Guilds of London Institute, or an equivalent qualification approved by the Council; or

(b) A Science or Engineering Degree of a British University, or equivalent qualification approved by the Council; or

(c) The Corporate Membership of the Institute of Electrical Engineers, or the Institution of Gas Engineers; or

(d) Achieved an outstanding position in Illuminating Engineering as a result of wide experience, or a specialised knowledge of some particular branch.

NOTES ON RECENT MEETINGS AND EVENTS

Programme for Next Session.

In spite of the uncertainties arising from war conditions, preparations for the 1940-41 session are being pursued. The Honorary Secretary will welcome suggestions from offers of papers or suggestions in regard to future meetings.

It is proposed that the opening event in the programme in London will be a demonstration-lecture by the new President, Professor J. T. MacGregor-Morris, who will take the opportunity to review scientific work on the Arc as a Standard of Light, and will deal particularly with some recent investigations on the humming effect.

It will be recalled that at the informal luncheon on May 7 the desirability of the Society devoting attention to problems of industrial lighting was strongly emphasised. The necessity for obscuration of windows of factories and the long hours of work under artificial light have involved new problems. These are to be considered at a meeting provisionally fixed to take place in London on October 22.

Similar arrangements for the consideration of this question early in the session are being made by the various Local Centres. In most cases dates during the month of October have already been assigned.

North-Western Centre.

SPECIAL MEETING, MAY 21.

A special meeting of members of the North-Western Local Centre took place in Manchester on May 21, when the President of the Society (Mr. F. C. Smith) presided.

In opening the proceedings the President referred to the effort made to maintain the Society's activities following the outbreak of war, and to the progress made by various Local Centres, notably those in the North Midland and Midland areas.

Suggestions for officers and committee for the coming session were then invited. As a result a committee of eleven members, with Mr. J. Taylor as chairman, Mr. H. E. Chancellor as vice-chairman, and Mr. A. H. Owen as hon. secretary, was formed. Mr. F. J. Palin consented to act as honorary treasurer and also to assist in secretarial work.

A resolution was passed thanking Mr. James Sellars for his past work as honorary secretary of the Centre, Mr. J. W. Howell, chairman of the North-Midland Centre, made some suggestions based on experience in his area. Mr. J. S. Dow, who had also come up from London specially for the meeting, referred to experience since the outbreak of war as illustrating the importance of perseverance and showing that useful work could be done by the Society under war conditions.

The President subsequently gave an address reviewing work done by the Society in connection with A.R.P. lighting, on which he replied to various queries. A vote of thanks to the President for his visit and to the Manchester Gas Corporation for permission to hold the meeting in their lecture theatre terminated the proceedings.

The List of Members.

Owing to the frequent changes of addresses of many members no printed list is being issued at the present time. So far as possible, however, all changes of addresses are being recorded, and all cases of members on active service whose membership is in suspension are being noted. Any members whose addresses have recently changed, or are uncertain owing to their being on active service, are requested to notify the hon. secretary.

New methods of recording names and addresses, which will simplify the separation of members connected with the various Local Centres, are being adopted. In addition, the year in which each member joined the Society has been traced and recorded, and this information will appear in future lists of members circulated.

The Library.

The attention of members is drawn to the Library which is still being maintained at 32, Victoria-street, London, S.W.1. The library may be inspected by members and the card index consulted at any time when committees are not in progress, and books may be borrowed on application to the hon. secretary.

A complete list of books in the Library has appeared in "The Transactions" (April, 1939; pp. 53-57). The following recent additions may be noted:—

SECTION No.	TITLE.	AUTHOR.	DATE.
1	Artificial Light and its Application in the Home	(Issued under the auspices of the I.E.S. (U.S.A.))	1932
11	The Story of the Lamp	Robins, F. W.	1939
23	An A.B.C. Guide to Glass ...	Reynolds, G. S., and Hughes, G. P.	1939
21	Papers presented at the I.C.I. Congress in Holland	.....	1939
2	Modern Factory Lighting ...	(Issued by the E.L.M.A. and E.D.A. conjointly)	1940

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SOME PHYSICAL PROBLEMS ASSOCIATED WITH GAS LIGHTING

By L. T. MINCHIN, B.Sc., M.Inst.Gas E. *(Member)*, A. B. DENSHAM, M.A., M.Inst.Gas E. and J. WRIGHT, B.Sc.

(Paper read at the meeting of the Illuminating Engineering Society held at Watson House, Townmead Road, Fulham, London, S.W. 6, on Tuesday, April 23rd, 1940).

Introduction.

The gas burner and the gas mantle are two very important features of every-day life which have received rather less than their due share of scientific attention in the past. Like the wheel and the decimal point, they have been taken for granted by the people who have had to use them.

If instead, however, one considers the exact mechanism by which the burner and the mantle perform their functions, one is struck by the complexity of the problem and the number of interesting possibilities which are revealed.

It is the purpose of this paper to discuss some of these problems, and if at times the subject seems somewhat remote from illuminating engineering it is hoped that the intrinsic interest of the problem will counterbalance this deficiency.

Part I.

The Entrainment of Air.

Every modern gas-lighting unit employs an aerated flame, i.e., one in which some air is premixed with the gas, to heat an incandescent mantle. This premixed air is sufficient to maintain the first stage of combustion inside the mantle where the hydrocarbons are oxidised to hydrogen and carbon monoxide. Secondary combustion to water and carbon dioxide takes place mostly in a thin film outside the mantle where the secondary air flows up to and round the hot surface(1), although a certain amount of flame usually projects from the top of the mantle.

The premixing of some air with the gas is essential in order to maintain oxidising conditions round the mantle (see Part III.), and to prevent the deposition of soot. It also has the effect of raising the temperature of the flame, and hence of increasing the light output; in general the flame temperature is at a maximum when the primary air is rather less than that required for complete combustion.

In nearly all cases of importance the pre-admixture of air with the gas is secured by permitting the gas to stream out through a fine orifice to which the air has access. There is reason to suppose that the actual mechanism by which this happens is somewhat as shown in Fig 1. When a jet of gas discharges into free air the surrounding air is set in motion by friction. Regarded kinetically this is equivalent to saying that the gas molecules transfer momentum by collision to the air molecules at the boundary of the jet. The mixing of air and gas is accelerated by small eddies, caused by this frictional resistance of the slowly moving air, and as a result

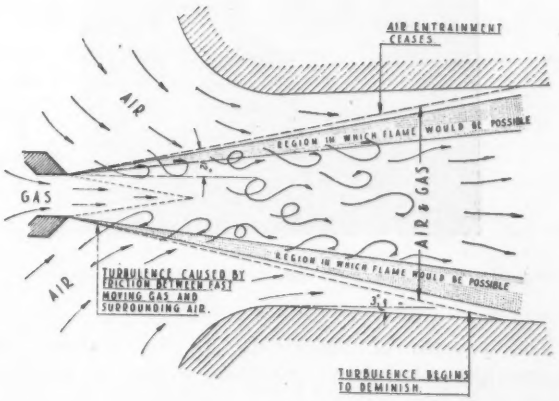

AIR ENTRAINMENT CEASES
AIR
REGION IN WHICH FLAME WOULD BE POSSIBLE
GAS
AIR & GAS
AIR
TURBULENCE CAUSED BY FRICTION BETWEEN FAST MOVING GAS AND SURROUNDING AIR.
REGION IN WHICH FLAME WOULD BE POSSIBLE
TURBULENCE BEGINS TO DEMINISH

Fig. 1.

the body of air and gas moves forward in the form of a cone with an angle of approximately 24° at the apex. This process of sharing momentum between jet and surrounding air—accompanied by a regular fall in the axial velocity—continues until it is stopped by the walls of the mixing tube which exclude any further air.

If one attempts to photograph this process by means of the "schlieren" apparatus the result is less regular, but agrees reasonably well with the above description. In particular the angle of divergence is quite close to the figure of 24° arrived at by Tollmien mathematically(2). The path of the air entrained can be made visible by a tiny flame or by small fila-

ments of heated platinum wire, as has been done in Fig. 2 ([22]). The gas in this case is not town's gas but hydrogen, which gives a result easier to photograph.

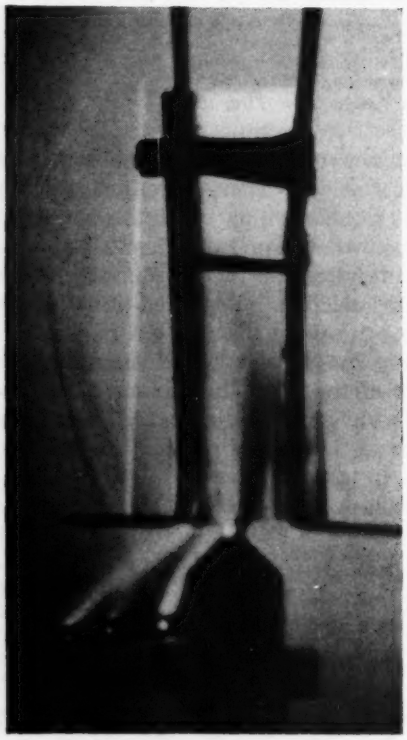


Fig. 2.

ENERGY CONSIDERATIONS.

The process of entraining air by transfer of momentum necessarily involves a loss of energy. Even if there is no loss of momentum whatever, i.e., if

$$M_1V_1 = (M_1+M_2)\ V_2$$

Where M_1 is mass of gas per unit time
M_2 is mass of air per unit time
V_1 is linear velocity of gas issuing from the injector orifice
V_2 is linear velocity of air gas mixture in flame ports

there is an inevitable loss in energy, equal to

$$\tfrac{1}{2}\ M_1V_1^2 - \tfrac{1}{2}\ (M_1+M_2)\ V_2^2$$
$$= \tfrac{1}{2}\ M_1V_1^2\ (1-\frac{M_1}{M_1+M_2})$$

This means, evidently, that the energy efficiency can never be higher than $\frac{M_1}{M_1+M_2}$ x 100 per cent.—a figure which becomes smaller the higher the proportion of air entrained. The lost energy is dissipated as dis-ordered motion, i.e., as heat. Actually, the efficiency obtained never reaches this limit, due to the existence of further practical energy losses at bends, sharp edges, rough walls, etc., and the most careful construction is needed to attain 50 per cent. of that theoretically possible. It is true that the kinetic energy of the outflowing air gas mixture is not of any value as energy *per se*, but it is nevertheless important to secure an adequate velocity for the mixed gases, sufficient to prevent the flame from lighting back. The maximum efficiency theoretically attainable if all the air required for combustion were to be entrained would be about 10 per cent., and a burner has been produced in the laboratory which, although having only half this efficiency, entrained this amount of air and gave a stable flame. In the ordinary commercial burner the energy losses are much greater, however, and complete aeration is not normally obtained at ordinary pressure. It is necessary to mention in passing that the use of this simple mechanical efficiency as a gauge of burner performance presents difficulties which have not yet been fully overcome. These principally arise from the fact that though the kinetic energy of the gas stream is the *cause* of the entrainment of air, the kinetic energy of the air-gas mixture is not the important *result* of this motive power. The result of interest to the designer is rather the amount of air entrained and the final velocity, and neither of these has the dimensions of energy.

Nevertheless the low mechanical efficiency of the bunsen burner has led to many attempts to devise other means of entraining air, some of which do more credit to the ingenuity than to the engineering experience of the inventors. We may mention in passing the Soleil d'Or, in which a thermopile heated by the waste gases was used to drive a small electric fan, and the Scott-Snell lamp—which achieved a certain success—in which a small hot-air motor was used for the same purpose. Other possibilities more recently considered include a gas-operated turbine working an air pump, and an arrangement somewhat similar to a dry gas meter in which bellows are mechanically coupled.

While it would be unwise to assume that such devices as this will never be perfected, there are very considerable practical difficulties to be overcome even in the most promising types.

In the case, however, of the bunsen type of air-injector, there are special difficulties peculiar to the

lighting burner. The burner nozzle gets extremely hot; this increases the flame velocity, and hence the necessary flame port velocity of the primary mixture, while the hot column of gases in the burner—being much lighter than air—tends to be pushed back up the burner by the pressure of the atmosphere. Further, the mantle itself opposes a resistance to the burning gases. For these reasons it is at present impracticable with a low-pressure lighting burner to work with an aeration higher than 2.3 : 1 (C.V.500 gas).

However, a higher aeration is obtainable by working with gas at higher pressures; the velocity of efflux of the gas from the injector nipple, and hence the momentum available for air injection, is proportional to the square root of the pressure of the gas above atmospheric. The considerable increase in efficiency which ensues* is due partly to this increase in aeration and partly to the increased momentum of the gases which makes it possible to force all the flame through the mantle fabric.

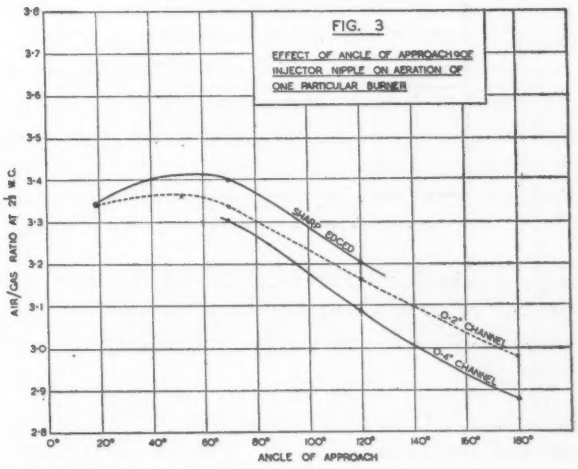
Even a relatively small increase in aeration would increase the efficiency of a low-pressure burner appreciably. During the past eighteen months a systematic research has been in progress at Watson House to determine the way in which the entrained air is influenced by the dimensions of the burner. Although this work is still far from completion some of the results which have already been established may be of interest.

Effect of Burner Shape.

At the entry into the burner is a gas jet which supplies the motive power for the air flow in which we are interested. The jet consists of a tube which is narrowed down to a small circular orifice, and the angle which the sides of this approach make with the axis was one of the first factors to be considered. Elementary considerations of stream-lining suggest that the form of a perforated flat disc which is often employed in practice must give rise to wasteful eddies, and a tapered approach should be better. On the other hand, if the taper were too gradual there would be a rise in friction with the sides since the channel would then become, in effect, a very long one. This analysis of the situation is confirmed by the experimental results shown in Fig. 3, from which it appears that the maximum air-entraining power is obtained when the approach is in the form of a 55° cone.

* Approximately 230 lumens/cu.ft./hr. for low pressure (3" w.g.) and 350 lumens/cu.ft./hr. for high pressure (80" w.g.).

We have already stated that the momentum of the air-gas mixture when the air-entraining process has come to a stop must still be sufficient to force it through the flame ports. Actually the resistance does not lie solely in the flame ports themselves, but also in the burner throat, tube, and bend, although the flame ports are usually the dominant factor. This is shown in Fig. 4. If the flame port area is increased from zero the aeration mounts rapidly at first, irrespective of the other resistances, in an approximately straight line. Ultimately a point is reached at which other resistances begin to play a part, and then further increases in the flame port area have less and less effect. Naturally, this flattening out of the curve takes place soonest when the resistance of the burner tube is highest in relation to the gas rate, and on the



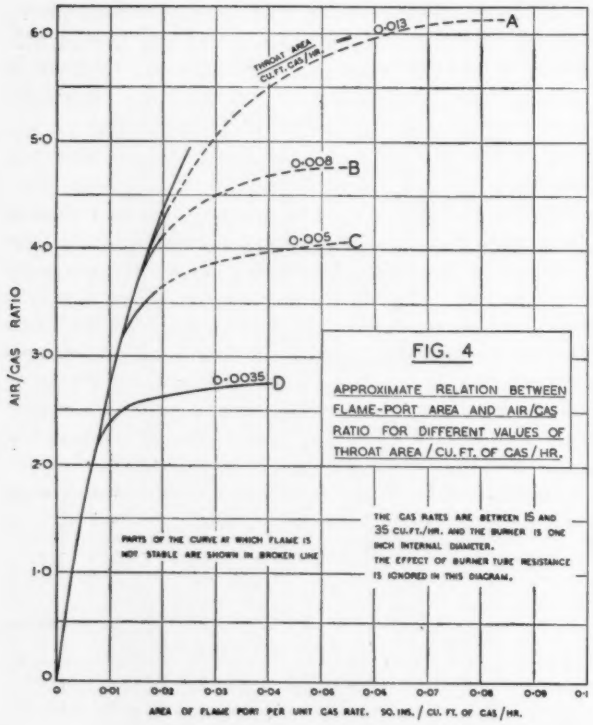
four curves shown in Fig. 4 the appropriate values of throat area per cubic foot of gas per hour have been indicated.

Part II.

Maintenance of a Stable Flame.

In the first section we have considered the first part of the bunsen burner's function—to provide a mixture of air and gas. When we come to consider the burning of this mixture a fresh set of considerations has to be studied. Chief amongst these is the velocity of flame propagation through the mixture and the manner in which this varies with the proportion of air to gas.

Conditions for a Stable Flame.—The velocity of flame is normally a maximum when the air-gas ratio is somewhat below that required for complete one-

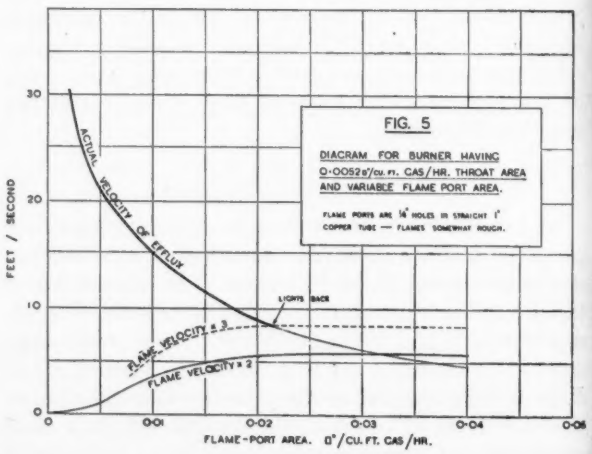

THROAT AREA / CU. FT. GAS / HR.
0·013
A
0·008
B
0·005
C
0·0035
D
AIR/GAS RATIO
AREA OF FLAME PORT PER UNIT GAS RATE. SQ. INS. / CU. FT. OF GAS / HR.
FIG. 4
APPROXIMATE RELATION BETWEEN FLAME-PORT AREA AND AIR/GAS RATIO FOR DIFFERENT VALUES OF THROAT AREA / CU. FT. OF GAS / HR.
PARTS OF THE CURVE AT WHICH FLAME IS NOT STABLE ARE SHOWN IN BROKEN LINE
THE GAS RATES ARE BETWEEN 15 AND 35 CU. FT. / HR. AND THE BURNER IS ONE INCH INTERNAL DIAMETER.
THE EFFECT OF BURNER TUBE RESISTANCE IS IGNORED IN THIS DIAGRAM.

stage combustion. For most town's gas this ratio has the value of about 4.3 and the maximum flame velocity occurs at about 3.7. Below about 1.7 the flame velocity is zero.

The normal stable bunsen flame represents a balance of two opposing velocities—the gas coming out and the flame going in. The size of the inner cone adjusts itself so that these two velocities are equal at its surface, and a reduction in flame speed or an increase in efflux velocity naturally leads to a longer cone. An opening of the air ports, even though it involves an increase of the velocity of efflux, normally leads to a shortening of the cone, because the flame velocity is increased far more in proportion. If, however, the aeration increase is obtained by enlarging the area of the flame ports—as in Fig. 4—the velocity of efflux will fall at the same time as the flame velocity rises, and a point will soon be reached at which the cone is too short to be stable. This point is represented by the transition from full line to broken line on the upper curves of Fig. 4. Unless a special flameproof burner head—which will be referred to later—is employed, the flame will not be stable in the regions represented by the broken line.

It was originally suggested by Bunsen that this lighting-back point occurred when the flame velocity in the burner tube was equal to the velocity of efflux. Subsequent work, however, has made it quite clear that this is not the case; instability usually occurs when the flame velocity is only about one-third or one-half of the efflux velocity. This is probably connected with the peculiar shape of the flame front in a tube noted by Coward and Hartwell,[3] who showed by photographs that the flame-front was not normally a simple disc but a convoluted surface having about twice the area of the cross-section of the tube. This means that the actual velocity of flame propagation is about twice the fundamental speed of the flame front and therefore approximately equal to the critical efflux velocity of the burner. The disparity between velocity of flame and the velocity of efflux is still further enhanced if the flow is rough and turbulent, giving rise to severe local variations in the speed of the mixture.

In Fig. 5 the velocity of efflux and the flame velocity have been calculated from curve C of Fig. 4 and from an experimental flame velocity curve. It will be seen that the lighting-back point in this case corresponds to a value of about three times the flame


FEET / SECOND
ACTUAL VELOCITY OF EFFLUX
LIGHTS BACK
FLAME VELOCITY × 3
FLAME VELOCITY × 2
FLAME-PORT AREA. □" / CU. FT. GAS / HR.
FIG. 5
DIAGRAM FOR BURNER HAVING 0·0052 □" / CU. FT. GAS / HR. THROAT AREA AND VARIABLE FLAME PORT AREA.
FLAME PORTS ARE ¼" HOLES IN STRAIGHT 1" COPPER TUBE — FLAMES SOMEWHAT ROUGH.

velocity. Had the flame ports been more carefully streamlined it would no doubt have been possible to have reached a lower figure—say, about twice the flame velocity.

Nature of the Inner Cone.—The inner cone of the bunsen flame—which can at times have such a solid appearance—owes its visibility to the chemiluminescence which accompanies the very intense chemical reactions taking place on the surface of that zone. Haber(4) has stated that the thickness of the surface in which primary combustion takes place is

only a fraction of a millimetre; and that the gases pass right through it in a thousandth of a second. In that short space of time nearly all the hydrocarbons are destroyed* and the space immediately above contains only CO, CO_2, H_2O, H_2, and N_2. The cone surface has a high electrical conductivity, due to the intense ionisation there(5).

Some of the Problems of the Bunsen Flame.

There has been much speculation as the cause of the characteristic shape of the bunsen cone. A number of workers have derived it by compounding velocities and drawing an envelope of the resultants(6). This gives a good picture of the sides of the cone—indeed the angle of the sides has been used for measuring the flame velocity—but does not explain the exact shape of the apex or the periphery. Most of these attempts have been based on the assumption that the issuing gas at the flame ports is in pure stream-line flow, but Benton has pointed out(7) that this is not always the case, and Khitrin(8) has attempted to allow for the change in velocity distribution resulting from the gases leaving the nozzle. It is not difficult, in any case, to arrive at a shape for the inner cone, which approximates to that observed in practice. In the simple case of a burner having uniform velocity across the flame port, the mechanism must be somewhat as in Fig 6. A hemispherical flame front spreading out from an ignition

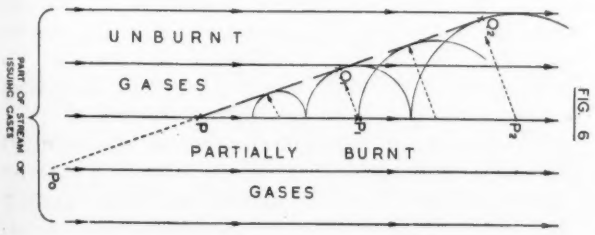


FIG. 6

point P (on the dividing line between burnt and unburnt gases) is swept up to a point P_1 by the motion of the gas whilst the flame front is expanding from P_1 to Q_1. By the time P_1 has reached P_2 the flame front has reached Q_2. Evidently this provides the basis for the formation of a cone of flame with sides parallel to the line PQ_2. It is not so clear, however, how the flame travels downwards to establish the base of the cone—i.e., towards P_0; probably this takes place through the zone of hot gases surrounding the inner cone and moving much more slowly. This is consistent with the well-known fact that when the outer mantle is absent—i.e., when the gas is completely burnt in the inner cone—there is a marked tendency for the cone to "blow off" the burner nozzle(9). This phenomenon is clearly connected with the difficulty of propagating downwards through the flame film, i.e., in the direction of Q_2—P_0 on the diagram—and is commonly overcome by the use of the "flame-retaining ring," which is a device which provides a small region of low efflux velocity round the periphery of the flame port.

The Flame-proof Burner Head.

It was mentioned earlier that burners could be made to operate at high aeration and low efflux velocities if flame-proof burner heads were used. There has lately been an increased interest in the possibility of using perforated metal plates in this way, and a recent investigation at these laboratories(10) established the relation of hole size and distance apart to "flame-proofness" under such circumstances.

The resistance to flame is a result of the subdivision to which the flame front is subjected by the perforations. If this results in the diameter of the unit flame being brought sufficiently low, the heat losses become very high in relation to the heat available from combustion, and the flame cannot maintain itself.

The formula connecting these factors is

$$S = \frac{1}{r} - \frac{2r}{b^2}$$

where S is a function indicative of the degree of flame resistance, r is the radius of each hole, and b is the distance apart between centres.

If a flame is produced on such a plate as this at a high aeration, it forms a fine blue mat over the metal, which on closer examination is seen to consist of a larger number of small blue cones with practically no outer flame mantle. The flame is very much scattered, and although very promising for some purposes, does not seem at present very suitable for use with a gas mantle as a source of light.

It is possible, however, that some way of using it for lighting may occur. In that case, the high aeration—7 to 1 or over can easily be obtained—should give rise to a higher flame temperature which would

* Decomposed and partially oxidised.

be expected to increase considerably the lighting efficiency attainable.

Part III.

The Luminosity of the Gas Mantle.

For the last forty years all gas lighting has had as its basis the light giving powers of a mixture of thoria and ceria when heated in a gas flame. This was introduced by Dr. Carl Auer von Welsbach in the last decade of the nineteenth century, and was eagerly seized upon by the Gas Industry because of the great increase in the light output which it made possible. Shapes of mantle, types of weave, design of burner have changed since that time, but the composition of the mantle has not been changed in any essential. Approximately 99 per cent. of thoria mixed with 1 per cent. ceria, with the addition of traces of a number of other substances for strengthening purposes, is the mixture employed, and the necessary lightness of structure is obtained by impregnating a woven organic fabric with the soluble salts and then burning away of the original fabric. What remains is a skeleton having the same microstructure as the original fabric but consisting solely of the sintered oxides.

The question "Why should this particular combination emit more light than any other?" does not seem to have greatly worried the inventor, though Simonini [11] has stated that Auer's staff were divided on this issue. The two explanations in vogue were:

(a) chemi-luminescence resulting from rapid alternate oxidation and reduction by the flame gases. (Both cerium and thorium can form lower oxides);

(b) a "kind of phosphorescence";

while yet a third view was that the luminosity was due to catalytic combustion on the surface of the mantle, producing thereby intense local heating.

However, little systematic work was done to test these theories, and the investigation of Le Chatelier and Boudouard [12], followed by the classic experiments of H. Rubens [13], cleared the ground and seemed to establish a simple thermal explanation for the phenomenon.

The luminosity of the Auer mixture was entirely due, they said, to selective radiation characteristics. It combined a very low overall emissivity—due to the thoria—with a very high emission in the blue region of the visible spectrum and a moderate emission at the red end—due to ceria. The low overall emissivity caused the mantle to reach a high temperature, while the emission in the visible range ensured that the colour of the light should be much whiter than the black body at the same temperature.

Reduction in the ceria content below normal causes the emissivity to fall, and although the temperature increases in consequence, the luminosity decreases. On the other hand, a rise in ceria content, although it causes an increase in the emissivity, causes a fall in temperature which more than counterbalances the first effect, and the net result is again a loss in light output.

Some twelve years later this explanation was confirmed by a paper written by Ives, Kingsbury, and Karrer [21], in the course of which a very full investigation of the radiation characteristics of different refractory oxides was described. From this it was concluded that there was little prospect of finding a better mixture than the one already in general use. Thoria had a much lower emissivity than any other oxide, and the radiation characteristics of ceria were greatly superior to any of the alternative "colourants" examined.

Other Unusual Features of Radiation from Mantle.

The radiation characteristics of the Auer mixture change with temperature and with the position it occupies in the flame. The first of these statements follows, indeed, from the fact that when cold it is white, whereas, when hot, it has a much higher emissivity in the blue than at the red end of the spectrum. Actually, the yellow colour of the mantle when hot can often be detected visually if a mantle is suddenly taken out of a flame. The "spider," a point at which the mantle is tied together, may then be seen to be yellow in colour for a moment.

The effect of a reducing flame seems to be to convert the mantle virtually into a "grey" body and thereby the temperature is lowered and the luminosity greatly diminished. This is normally ascribed to the formation of a sub-oxide of cerium—possibly Ce_4O_7—and Ives [21] claims to have obtained a grey specimen by heating a ceria-rich mantle in a reducing atmosphere and then cooling it in the same gases to prevent re-oxidation.

The inner cone of a bunsen flame is, of course, a reducing region, and it is familiar to all workers with gas light that if the inner cone projects through the mantle it causes the fabric to become relatively non-luminous. The rapidity with which the glow of an ordinary mantle will fluctuate as the flame impinging upon it varies from oxidising to reducing is greater than one would have expected from a change

in chemical composition, but it is difficult to test such an hypothesis practically.

Excitation of Luminescence by Flame.[14]

Of recent years the problem of the glowing of a gas mantle has become less simple because of the realisation that in some cases it is possible for undoubted luminescence to be excited by contact with flame. Thus, when Balmain, in 1842 ([15]), first prepared boron nitride he discovered that it showed an "elegant green phosphorescence" in the outside fringe of a flame. If the experiment is repeated today one observes that the greenish-blue glow starts first as the specimen heats up. When it has become quite bright the red of normal incandescence begins to show itself, and only when the substance has reached a bright red heat is the green colour masked. It is claimed by Nichols and his collaborators that such a luminescence persists above red heat in some substances. Zinc oxide at 800°C. is said, for example, to glow 115 times as brightly if in contact with flame than if heated electrically. Although Nichols never claimed that the glowing of the gas mantle was an example of the same phenomenon, the parallelism is often striking. Niobium oxide, for instance, luminesces green in the oxidising flame but radiates in a reducing flame as a black body. Again, this "cando-luminescence," as it is called by Nichols, normally occurs not in pure substances but in substances which have been "activated" by the addition of a small amount of a second substance.

Theory of "Cando-Luminescence."

So far this is a matter of conjecture only, since no one has yet put forward any theory which is adequately supported by experimental evidence.

Paneth ([16]) and Tiede ([17]) both discuss the question, considering the alternative theories of

(a) excitation by ultra-violet emission from the flames;

(b) excitation by ions contained in the flame gases;

while Goodeve([18]) suggests that atoms and free radicals present in the flame are enabled to combine and give up their excess energy by the presence of the solid, this energy being emitted as light radiation.

According to this explanation, when two molecules A, B, (for example, O_2, H_2) react in a flame they momentarily form a complex containing all the energy of reaction.

$$A+B \longrightarrow AB^*$$

This activated complex persists for an appreciable, though, of course, very minute, period of time, owing to certain difficulties in getting rid of the excess energy. It could radiate the energy, but this necessitates a relatively slow internal rearrangement. More usually it hands on the energy to another molecule, but this cannot occur unless the other molecule is in a suitable internal condition to receive it at the moment of collision.

Solid surfaces, however, can take over this excess energy much more easily than gaseous molecules. Provided that the solid is a better radiator than conductor, any excess energy taken over from the activated complex will be radiated by the solid. Thus, in effect, the solid is in thermal equilibrium with the most active (i.e., the hottest) particles in the flame, and the radiation will be greater than corresponds to the average temperature.

This conception is in no way contrary to the Second Law of Thermodynamics, but is analogous to other forms of chemi-luminescence, where the energy of reaction is converted directly to radiant energy and is not used to heat up a body which in turn emits purely thermal radiation.

An interesting phenomenon which supports this theory is the glowing of certain substances when exposed to active nitrogen or ozone.

Tiede and Schleede([19]) point out that this only occurs in substances which also show luminescence under flame excitation, and that some substances—such as Sidot blende—which are strongly luminescent to ultra-violet light, cannot be excited either by flame or by active nitrogen. It is also known that the Auer mixture is a good catalyst for the oxidation of coal gas—better, for example, than the same two oxides mixed in any other proportion.

Whatever be the true explanation, there can be no doubt that the phenomenon opens up new vistas for gas lighting, which may, perhaps, one day lead to a great increase in lighting efficiency of gas lighting.

On the purely thermal radiation theory of gas lighting there appeared very little prospect of ever increasing efficiency more than, say, 100 per cent.—an amount which, though of course desirable, would still leave the energy efficiency deplorably low. The present figure for a low-pressure lamp is about 0.2 per cent.([1]), whereas Evans and Polanyi ([20]) have recorded as high a value as 40 per cent. for the chemiluminescence resulting from the union of sodium and iodine under special conditions.

Once, therefore, the phenomenon of the

incandescent mantle is established as being of the nature of luminescence the barriers are down, and there is no longer any theoretical reason why lighting efficiency should not be advanced ten- or a hundred-fold.

Acknowledgements.

In conclusion, the authors wish to thank their colleagues at Watson House for their help and criticism, and also to express their gratitude to the Governor and Directors of the Gas Light and Coke Company for permission to publish this paper.

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DISCUSSION

Mr. C. A. MASTERMAN, after welcoming the members of the Society to Watson House on behalf of the governor and directors of the Gas Light and Coke Company, went on to congratulate the authors, and especially Mr. L. T. Minchin, on the success of the demonstrations.

The paper, instead of stressing the problems associated with gas lighting as inferred by the title, took the more optimistic line of showing the directions in which scientific knowledge indicates the possibility of further improvements.

Like many other things of everyday use, the bunsen burner has become so familiar that there has been a danger of overlooking opportunity for improvement by going back to first principles. The authors refer to a burner of different physical characteristics such as to enable an air-gas ratio up to 7:1 to be maintained with a stable flame—a really revolutionary advance. It is too early to say whether this burner can satisfactorily be used for gas lighting, but it is significant that when the air gas ratio is increased as it is by the use of high pressure gas very much higher lighting efficiencies are obtained.

The second part of the paper refers to long-term investigations of an even more fundamental character. Attention is drawn to phenomena in which the combustion process appears to be showing the direct development of light from the energy of reaction without intermediate degradation into heat. Along these lines the theoretical limits to lighting efficiency are, of course, many times higher than where the energy is heat energy alone.

The work referred to in the paper is not, of course, primarily designed for the present "black-out" period, but is directed towards improving service to the community in the difficult period which lies ahead after the war. The emergency laws and regulations under which we live, while they impose a physical black-out, cannot, and should not, impose a black-out of scientific endeavour, the results of which will be all the more welcome at the end of the present emergency.

Mr. W. E. BENTON congratulated the authors on the presentation of their subject. He thought that they need not have followed so closely the conventional treatment of aeration, particularly in the use of momentum, which is a vector not a scalar quantity. One could not speak of momentum being carried like dust through the tortuous passages of an atmospheric burner. There is no such thing as the momentum of a stream, but one may use "the rate of flow of momentum" in Eulerian equations, where it is proportional to dynamic pressure.

Personally he worked out aeration equations by regarding the flow as a rigid system and constructing an equation of forces. Beyond the burner-throat one

adjusted the equations of forces from point to point to suit changes of cross section and direction.

In the authors' treatment of the conditions inside the burner no reference was made to static pressure. No energy equation could be constructed without taking into account the potential energy derivable from pressure. When an injector entrains air into a straight parallel-tube the resistance of the walls can only be overcome by robbing the static pressure, but no allowance for this pressure is made in the momentum equations.

He did not agree with the authors' explanation of the increased resistance offered by a heated burner. If the loss of aeration in an inverted burner were due to change of density one would expect to find a gain of aeration by reinverting it, but the increased resistance was almost independent of the direction of the tube. The fact is that the air-gas mixture when heated must expand and must therefore accelerate and in so doing must rob the static pressure. On this basis the loss of aeration could be calculated without difficulty.

Discussing the shape of the inner cone of the bunsen burner one should aim to produce a uniform velocity distribution, maintained over the short distance for which it was required. Large eddies should be avoided, but eddy motion was not necessarily an evil thing; it was, in fact, an essential.

In conclusion, Mr. Benton illustrated his conception of the construction of the inner cone of the flame by the analogy of the approach of fish to a river mouth, pointing out particularly how by this means the process at the base of the cone, where the mixture was being constantly re-ignited from the outer flame, could be pictured.

At this stage the President presented a written communication from Mr. E. C. W. Smith, of Leeds University.

Mr. E. C. W. Smith (*communicated*): I should like to congratulate the authors on this valuable summary of problems associated with gas lighting and forecast of the probable direction of future development. The discussion of the theory of the Welsbach mantle and of the possible application of luminescent substances to the more efficient utilisation of the energy of combustion of gas is particularly interesting. It seems very probable that development along these lines has actually been hampered during this century by the universal acceptance of the laws of black body radiation. The validity of these laws remains unquestioned, but it must be fully realised that they apply only to matter which is radiating while in thermal equilibrium with its surroundings. It is recognised now that when atoms and molecules undergo chemical change, some of the energy of chemical reaction is concentrated in one form or another in particular species, and a finite time may elapse before such species come into thermal equilibrium with the remainder of the system. This energy which is locked up for a time in this way may be many times the mean energy, or temperature, of the system as a whole. The example given in this paper is a special case of a rather more general phenomenon. Thus it is now recognised that a solid body which can interact in some way with these particles in a flame which are possessed of energy in excess of the mean energy of the system, as measured by the flame temperature, could hence radiate light in excess of that from a perfect radiator at the measured flame temperature.

I have commenced, at Leeds University, a re-examination of the phenomenon of "cando-luminescence." So far attention has been directed to the higher temperature ranges in which, according to Nichols and his co-workers, luminescent radiation supplements that due to normal incandescence, leading to a total emission several times that of a black body. It must be realised that the light output which is claimed for these substances at temperatures below red heat is very small in magnitude, and hence the emission at higher temperatures is much more likely to be of practical importance.

A repetition of some of Nichols's experiments shows qualitative agreement with his measurements, but direct determination with very fine thermocouples, .001″ diameter, placed immediately beneath the heated surfaces, shows that his assumptions with regard to the temperature of the surfaces are unjustified. Further, all the substances examined to date have shown an apparent emissivity which is constant within experimental error over the temperature range examined, and is also approximately equal to the accepted value for heating in the absence of flame, showing that in these particular cases luminescence can only play a negligibly small part in the total light production.

Although these preliminary results are somewhat disappointing, they apply directly only to the relatively few substances which have so far been examined, and only to the higher temperature ranges. It is felt that they should be regarded as an incentive

to rather than a deterrent from further work along these lines, since, as very rightly stressed by the authors, it is only by the application of luminescent radiation that there appears to be any possibility of a considerable increase in the efficiency of gas lighting. The application of discharge tube lighting in the electrical industry to replace the incandescent filament is a precisely analogous case of conversion of the available energy, in this case electrical energy, directly to radiation, without the intermediate stage of "degradation" to thermal energy.

Mr. G. H. WILSON inquired of the authors whether the velocity of efflux figures shown in Fig. 9 had been obtained by calculation from the input to the burner and the size of the orifice or by an exploration. He also asked what temperatures would be found in the flame if it were explored, say, by a thermocouple. He had an idea that if the flame were explored in that way it would be found to be hotter near the blue cone and, if that were so, one would expect the ordinary thermal understanding of the problem that if the mantle were brought into the same place it would also look brighter. Could the authors clarify this point?

Reference had been made to a burner which entrained a very much greater amount of air than the usual type of burner, and Mr. Wilson asked if the different physical characteristics were the chief advantages. It would be interesting to know the difference between this burner and the Meker burner.

Continuing, Mr. Wilson said he had always been fascinated by the type of lamp in which oil was burned with a non-luminous flame, which was hot enough to render a mantle incandescent. He had never understood how it was done and, as the chance of the Society having a paper on this subject was rather remote, he wished to ask the authors to explain in a few words how this non-luminous flame could be obtained in a simple wick burner without any air being pumped in, and how the mantle, which was of more open texture than the gas mantle, was made luminous.

Mr. J. S. Dow suggested that the authors were perhaps a little pessimistic in inferring that, on the purely thermal radiation theory of gas lighting, one could hardly hope to increase the efficiency by more than 100 per cent. There were, as the authors had shown, great inherent losses. Combustion was not complete or ideal. Of the heat generated only a part activated the burner. The proportion of the latent energy in the gas entering the burner which ultimately appeared as visible light was doubtless minute. He seemed to recall some experiments of Dr. Rubens and others, in which a distinction was drawn between the ultimate or "all in" efficiency in the above sense and the luminous efficiency representing the proportion of the energy radiated by the mantle in a luminous form. If the 0.2 per cent. mentioned by the authors represented luminous efficiency thus defined, and derived in a manner comparable with that applied to electric lamps (i.e., by inspection of energy distribution curve), then the radiant efficiency, in which account was taken of all possible losses, would presumably be very much less still.

This, however, properly regarded, was a cause of encouragement, as it showed how very great was the theoretical margin for possible improvement.

Mr. S. S. BEGGS said he imagined that the question of the flame firing back was concerned largely with the velocity of the mixture where the air was entrained. Looking at the burners in the laboratory at Watson House he said some seemed to be working at higher pressures than others so that they were applicable only to special cases. However, could the authors explain simply how they managed to get what seemed to be three types of injection giving different results and yet looking very much the same? There was one type of injector which immediately fired back if a flame was applied to the air inlet. There was another in which this did not happen and the gas did not ignite at this inlet; and there was a third injector in which, if a flame was applied to the air port, the flame travelled along to the top of the burner and the gas lighted up where it was wanted. Could the authors explain how these three different effects were obtained?

The new type of burner with the gauze front, which had been demonstrated, reminded him of the experiments conducted at school when they were told about the Davy safety lamp. It was usually explained that the Davy lamp was a safety lamp because the flame was cooled by the gauze and would not travel through it. In the case of the author's burner it was implied in the paper that there was no firing back because the flame was cooled by the perforated plate. Surely, if the flame were cooled it resulted in a less efficient light source? It rather seemed to him that there were two opposing ideas here. In the first place the authors were trying to get a hotter flame, and in the second they cooled it down in a special burner. They were trying to get

a hotter flame to obtain better incandescence from heating of the mantle and yet they were using a device which was similar in principle to the Davy device for cooling the flame.

Dr. S. ENGLISH remarked that the paper carried him back to the days when he was specially interested in gas burners, and one little incident in particular. About twenty years ago he was working on glass melting furnaces in which compressed air was used and, of course, the noise was so terrible that it was impossible to hear oneself speak. As these furnaces were situated in the middle of a densely populated neighbourhood, it could be imagined that those responsible for running them were not popular. This was particularly the case when the furnaces were run at night, and a request was made that the noise should be reduced. After some consideration it was decided to use a high-speed fan instead of a noisy blower and by means of an injector premix the gas and air: the result was a good temperature and a silent flame. This arrangement ran beautifully for a long time until one night the belt driving the fan broke and there was a noise like a bomb dropping. The experiment was therefore abandoned.

Passing to the paper Dr. English said he wished to raise one or two points of, perhaps, academic interest and some others which might seem of a quibbling nature but he would like to assure the authors that these would in no way detract from his admiration for the work they had done.

When the authors spoke of the kinetic energy of the mixed gas and air in the burner tube he understood them to say that there was such a loss of energy due to the entrainment of the air that the burner could not be more than 10 per cent. efficient. Was that really so, or was there not a little bit of loose wording about this? The efficiency of the burner did not depend on the kinetic energy that was put into it but on the chemical energy of the substances burned and therefore the efficiency of a burner might be very much higher than 10 per cent.

With regard to injector shape, he had been surprised to hear from the authors that that matter had not previously been particularly carefully studied. Surely that was one of the matters that any burner manufacturer should have looked into straightaway.

Commenting on the burner of the Meker type, and the 7 to 1 air-gas ratio, Dr. English recalled that Mr. Minchin, in presenting the paper, had said that the ideal air-gas ratio was 4½ or 5 to 1. If that were so, why go above the ideal. What was the difference between this burner and the Meker, how was the higher aeration and higher temperature obtained, and what was the advantage of this burner over the Meker?

Referring to the boron nitride experiment, Dr. English asked if Mr. Minchin was really pleased with the explanation he had put forward. Was it the volatilisation of the boron nitride which coloured the flame? If not, where did the energy producing the luminescence come from?

Dr. T. H. HARRISON (*communicated*): The demonstration of the existence of a "cando-luminescence" undoubtedly suggests that there is here a phenomenon that demands considerable scientific investigation, even though there may be no immediate prospect of its practical application.

Two lines of investigation seem to be indicated, viz.:—

(1) An inquiry into the exact sources of the quanta of luminescent radiation and the positions of these sources.

(2) An inquiry into the mechanism of the excitation of these sources and into the energetics of this mechanism.

Regarding (1), and presuming that it is boron or boron nitride molecules that are emitting the luminescence, it is important to find out whether these atoms at the moment they emit their quanta are situated within or outside the solid surface of the boron nitride. Do these atoms or molecules emit fluorescent radiation before or after they have been sputtered from the solid surface? This matter is important because those atoms that remain in the surface are obviously, under the conditions of the demonstration, at a temperature below red heat, while the green luminescence must be at least several hundred times as bright as any green light that could be attributed to ordinary temperature-radiation. This same remark might possibly also apply even to molecules just outside the solid surface; for the flame temperature in close proximity to the solid surface cannot be very high. The demonstration seemed to indicate that while a certain amount of the luminescence was visible in the flame, the main part proceeded from, or from very close to, the solid boron nitride, whose surface exactly resembled any other surface of luminescent material. Appearances, however, are sometimes

deceptive, and it is thought that very close investigation is needed on this matter. Should further investigation show that it is the solid surface that fluoresces, then, indeed, the demonstration might rightly be considered as one of an entirely new kind of lamp, however inefficient and unpractical this lamp may be at present.

Regarding (2), where does the stimulation come from? To say that it comes from the flame is not nearly precise enough. Will a pure hydrogen flame produce the effect? If so, the effect of bombardment of carbon atoms may be left out of account. The effect of the flame on the solid surface would then be really one of a simultaneous bombardment with hydrogen and oxygen atoms or ions. It might be possible to arrange such a bombardment by the agency of some means other than the flame. Would this form of bombardment produce the luminescence? Experiments on these lines, together with theoretical work based on the results, might well indicate to what extent progress is barred by theoretical considerations, and narrow the path along which work might usefully progress.

Mr. L. T. MINCHIN, replying to the discussion, said the authors failed to understand Mr. Benton's objection to the use of momentum and the Eulerian equations. It seemed that this method of approach gave a better insight into the actual mechanism of air entrainment.

Mr. Benton's method of regarding the flow as a rigid body afforded an ingenious attempt to calculate the aeration of practical burners, but he was not satisfied that this was entirely sound, and it did not always give the correct results. The authors hoped to make a more thorough investigation of this later on.

Static pressure was certainly of great importance, but this paper was not intended to be a detailed discussion of the whole field.

Mr. Benton was certainly correct in attributing the resistance of a lighting burner to expansion, more than to chimney pull.

It had been very interesting to hear from Mr. E. C. W. Smith that after repeating Nichols's experiments on oxides he had found, as they (the authors) had suspected, that Nichols did not take nearly enough care to make sure what the temperatures of his oxides were. In the view of the authors, the experiments of Nichols were very loosely carried out so far as the temperature was concerned, and yet he worked out very carefully the emissivity to the second decimal place when he was working at 1,500 deg. C., which was ridiculous. Far and away better work was done in Germany by Tiede, Paneth, and their colleagues prior to 1925.

Replying to questions put by Mr. Wilson, he said that the velocity of efflux was measured, or rather computed, from the air mixture velocity, and it was described in the paper as the average velocity of the mixture rather than the velocity at any one point in the stream. The reference to the flame temperature was an interesting point, and there was a passage in Haber's book on " Thermodynamics of Technical Gas Reactions " in which it was stated that the blue cone was not, as was generally believed, the hottest part of the flame. Haber quoted measurements showing that the hottest part was well above the cone in the region where secondary combustion was taking place. A crucible placed immediately over the inner cone was inevitably more deeply immersed in the flame than one placed higher, and this may have given rise to the impression that the point of the cone is the region of highest temperature.

Many people had mentioned the high aeration burner, and queried its advantages. Reference had also been made, in this connection, to the Meker burner, but this latter burner worked at a much lower aeration. It did not have a flameproof head, and if the efflux velocity was reduced it lit back quite easily. That was not so with the burner referred to in the paper, whatever the aeration. It had been asked whether there was a cooling effect on the principle of the Davy lamp, but according to the best authorities on the subject the old explanation of the Davy lamp—that the gauze simply cooled the flame—was not tenable. The orthodox explanation to-day was that if one took a single hole and tried to let a flame go through, it emerged as an element of flame —probably a hemisphere—at the bottom. If this hemisphere was sufficiently small the flame would go out, and it had to be over a certain size in order to persist. Before the Davy lamp, the flint mill was used in coal mines as a source of light, because so long as the particles were small enough they would not ignite an explosive mixture, as any flame formed was too small to persist. The smaller the volume of flame the bigger the heat losses in proportion to the heat energy available, and that was why the flame went out if it was too small. In a paper published last year by one of the present authors, it was pointed out that if the holes were very close together the emerging flame element had a better chance of survival, and therefore the holes had to be made smaller if flameproofness was to be maintained. There was

a formula in the paper which showed the relation of hole size to distance apart of holes.

The reason why an air/gas ratio of more than 5 to 1 was obtained with this burner was partly because it could not be helped and partly because it was an advantage in some cases when it was desired to exclude all secondary air. With the present burner it was possible to screen off completely all secondary air and still get very good combustion inside. This was an advantage in some applications. Further, it was useful to have a margin, so that a slight fall in aeration would not immediately result in bad combustion. Therefore, an aeration over the 5 to 1 ratio was necessary in order to get reliable operation, although from the point of view of temperature of the flame it was better to have a 5 to 1 ratio.

As to the incandescent oil type of lamp, it might be possible to persuade a representative of the company concerned to give a paper on it, and he could put the secretary in touch with one gentleman on the staff of that company who might be willing to do so. He believed that a sort of air lift pump was used, in which the vaporisation of paraffin in a tube at one spot by a pilot flame started a syphon into operation.*

The efficiency of 0.2 per cent. for the mantle had been commented upon but although perhaps that was on the low side, it gave an idea of the order of efficiency. It had probably increased in recent years. This figure was based simply on the ratio of the heat input to that which would be required if all the energy put into it were re-emitted in the yellow-green wavelength (which lies at the point of maximum sensitivity). If, however, white light was regarded as 100 per cent., then the efficiency of the gas mantle on this basis was much greater, i.e., about 1.5 per cent. Although there were a number of heat losses in a mantle, the direct thermal radiation was about 40 per cent. of the heat input, and if all the losses mentioned by Mr. Dow were removed entirely, the thermal efficiency would be increased to about 90 per cent., and that would only double the light efficiency.

The question of lighting back—raised by Mr. Beggs—was a big subject, and could not be dealt with in this reply. A paper dealing fully with this had been prepared and would no doubt be published later.

In reply to Dr. English on the question of volatilisation of the boron nitride, Mr. Minchin said that the green-blue luminescence definitely came from the part of the boron nitride stuck on to the brick, as was seen in the demonstration he had given of this. The greenish colour given to the flame when boron compounds were present was quite a different phenomenon, although there might be some relation. The point was that the greenish-blue luminescence started immediately the flame impinged on the brick, and it was only after the glow had been going on for some time that the ordinary incandescence started. There was no doubt that the light energy must come from the chemical energy of combustion between the gases in the flame. Further experiment might indicate there was some change of state, but personally he did not think that was the case.

Dr. Harrison had asked some searching questions on the luminescence phenomenon which could best be answered by reference to two recent papers in the Transactions of the Faraday Society (ref. 14). A pure hydrogen flame would certainly produce the effect, as would also the flames of alcohol, carbon bisulphide and chlorine burning in hydrogen. This suggested that it was some feature common to all flames which was responsible for the effect. Activated radicals or ions seemed to be the chief alternatives; and there was some evidence that the former was the actual motivator. This view was mainly based on the phenomenon noticed by a number of workers that active nitrogen, issuing from a discharge tube, causes a luminescent glow in certain substances; and Tiede and Schleede (ref. 19) claim that the list of substances exhibiting this property includes nearly all of the flame-luminescent substances but *excludes* some notable photo-luminescent materials.

Mr. G. H. WILSON, proposing a vote of thanks to the authors, said it had been his conviction for some time that a paper on the physical properties associated with the gas burner would make a very attractive evening, and the paper by Messrs. Minchin, Densham, and Wright had exceeded his expectations,

*I have since discussed the matter with one of their representatives, Mr. Richardson, to whom I am indebted for the following additional information:—

> There are two principal types of oil lamp using incandescent mantles. The one referred to in my reply was the pressure type, which has no wick and operates in a similar fashion to the familiar "Primus" stove. More important, however, is the type to which Mr. Wilson was evidently referring, which is furnished with an annular wick. The use of a glass chimney enables a stream of air to be directed on to the wick from the inside and the outside of the annulus, and this forces the flame to burn above the wick, where the mantle is situated, with a blue non-sooty flame.

because it had not only brought the subject up to date but had been accompanied by splendid demonstrations and experiments.

At the same time, continued Mr. Wilson, he wished to express the appreciation of all those attending the meeting for the hospitality which had been extended to them by the Gas Light and Coke Company in being afforded the opportunity of inspecting the laboratories of Watson House, and also in being entertained to tea afterwards.

The votes of thanks were carried with hearty acclamation, and the President said the appreciation of the visitors would be conveyed to the governor and directors of the Gas Light and Coke Company.

Transfers from Country Membership to Corporate Membership

The following have made application to be transferred from the class of Country membership to the class of Corporate membership in the Society:—

Anderson, J. M.	43, Church Road, Giffnock, RENFREWSHIRE.
Allderidge, C. J.	10, Boscobel Road, WALSALL.
Broadfoot, E.	181, Arisaih Drive, GLASGOW.
Bayliff, T.	71, Amulree Street, Shettleston, GLASGOW.
Cartwright, T. D.	195, St. Vincent Street, GLASGOW, C.2.
Cassels, T. M.	ELMA Lighting Service Bureau, 29, St. Vincent Place, GLASGOW, C.1.
Caunt, C. S.	62, Thackerays Lane, Woodthorpe, NOTTINGHAM.
Drake, W. E. J.	Metropolitan-Vickers Electrical Co., Ltd., 1, Kingsway, LONDON, W.C.2.
Forbes, B. Stuart	Cryselco, Ltd., 211, West Campbell Street, GLASGOW, C.2.
Gavin, T.	B.T.H. Company, Ltd., 53, Pitt Street, GLASGOW, C.2.
Illingworth, T.	79, St. Helen's Road, Booterstown, Co. DUBLIN.
Kidd, A. G.	Engineers' Dept., John Players and Sons, NOTTINGHAM.
Lindsay, A.	173, Bath Street, GLASGOW, C.2.
MacNaughton, V. P.	40, Wellington Street, GLASGOW.
Rankin, A. M.	20, James Street, GLASGOW, S.E.
Smith, P. E.	21, Ruthven Avenue, Giffnock, GLASGOW.
Scott, J. H.	88-90, York Street, GLASGOW, C.2.
Tate, W. K.	Wandsworth and District Gas Company, Fairfield Street, WANDSWORTH, S.W.18.
Thwaite, W., Sen.	County Architect's Office, Shire Hall, NOTTINGHAM.

FELLOWSHIP

A considerable number of applications for transfer to the class of Fellows have been received since the first list was issued in "The Transactions" (No. 5, June, 1940, p. 73). A number of these applications are still under consideration. The Board of Fellows has, however, recommended the election of the following as Fellows of the Society, and this recommendation has been approved by the Council:—

Bicknell, C. R.	1, Oakway, Shortlands, KENT.
Hetherington, W.	24, The Crescent, Alwoodley Park, LEEDS.
Hale, F. M.	208, Castlemilk-road, King's Park, GLASGOW, S.4.
Jepson, A. E.	12, River Court, Portsmouth-road, Surbiton, SURREY.
McGibbon, A. R.	108, Cassiobury Park-avenue, Watford, HERTS.
Maxted, R.	1, Whitehall-road, RUGBY.
Parker, J. E.	50, Hillcroft-avenue, Pinner, MIDDX.
Parsons, Sir John Herbert, C.B.E., F.R.S.	54, Queen Anne-street, LONDON, W.1.
Sayers, R. P.	24, Woodland-rise, Greenford, MIDDX.
Walker, Frank	Crosscliffe, Shelford-road, Radcliffe-on-Trent, NOTTS.
Wilkie, T.	65, Dumbleton-avenue, LEICESTER.
Wilson, Sir Duncan, C.V.O., C.B.E.	Catt's Cottage, Underriver, Sevenoaks, KENT.

The attention of the Board has been drawn to the position of certain country members, otherwise qualified for Fellowship, who have not yet been Corporate members for the prescribed period of two years. It appears that in the case of some country members hardship is imposed by this condition. The following temporary procedure has been proposed by the Board and approved by the Council:—

> "In the case of any country member of the Society of two years' standing or more a transfer to Corporate membership may be considered to date from a period two years prior to the date of application on his behalf for Fellowship, provided that any additional subscription involved is duly paid to the Society."

This arrangement will continue in force for the present year (1940) only, after which only applications from Corporate members of two years' standing will be considered.

The Library.

The following has been added to the list of books in the Library ("Transactions," Apr., 1939, pp. 53-57):—

SECTION No.	TITLE.	AUTHOR.	DATE.
1	Vocabulary of Terms Connected with Illuminating Engineering (with versions in Dutch, English, French, German, and Esperanto).	Edited by the Secretary of the Dutch National Committee on Illumination.	1940

Printed by ARGUS PRESS, LTD., Temple-avenue and Tudor-street, London, E.C.4, England.

THE NEW UNIT OF LIGHT

By J. W. T. WALSH, M.A., D.Sc., M.I.E.E. *(Fellow)*

(Paper read at the Meeting of the Illuminating Engineering Society, on Tuesday, May 7th, 1940.)

Historical.

The first successful efforts to establish an international unit of luminous intensity were made in the early years of the present century(1) and these culminated in the agreement published in 1909 jointly

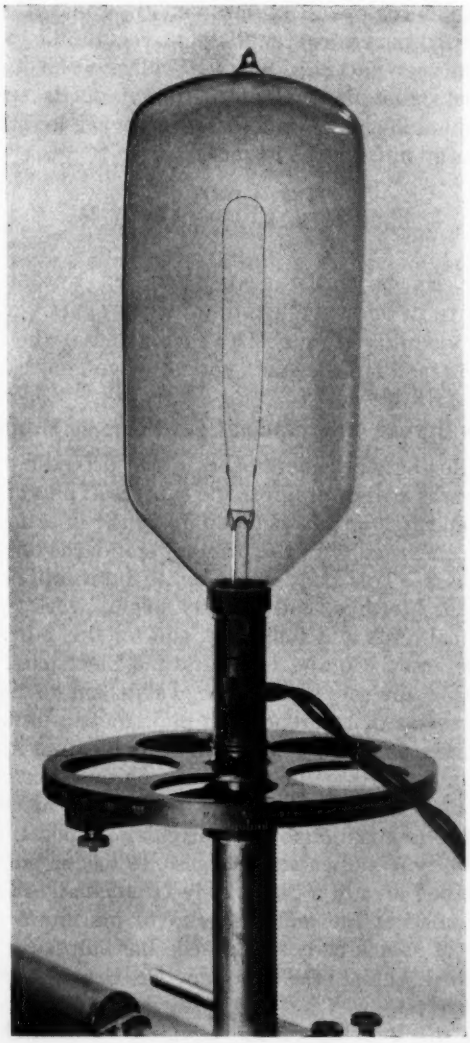

FIG. 1.

by the Bureau of Standards, the Laboratoire Central d'Electricité, and the National Physical Laboratory(2). By this agreement the comparatively small differences between the units then in use in the United States, France, and Great Britain respectively were removed and a common unit was, from April 1, 1909, adopted in all three countries. Germany was not a party to this agreement and in that country and some others the Hefnerkerze continued to be employed. Its value was stated, in the published agreement of 1909, to be nine-tenths of the unit set up by that agreement. Although the agreed unit was derived from flame standards, principally the Vernon Harcourt ten-candle pentane lamp, it was maintained at the three national laboratories by means of carbon filament electric lamps. At the National Physical Laboratory these lamps were a group of eleven Fleming-Ediswan sub-standards, one of which is shown in Fig. 1.

At the first post-war meeting of the International Commission on Illumination, held in 1921, the unit referred to in the 1909 agreement was adopted officially by the Commission and given the name of the "International Candle." The text of the resolution by which this was done is as follows:—

> L'unité d'intensité lumineuse est la Bougie Internationale telle qu'elle résulte des accords intervenus entre les trois laboratoires nationaux d'étalonnage de France, de Grande-Bretagne et des Etats-Unis en 1909.* Cette unité a été conservée depuis lors au moyen de lampes à incandescence électriques, dans ces laboratoires qui restent chargés de sa conservation.

As Germany was not represented at the 1921 meeting of the I.C.I., that country did not accept the so-called "International Candle" and the Hefnerkerze continued in use as before.

Both the "International Candle" and the Hefnerkerze were maintained by means of lamps operating at colour temperatures much lower than those of the light sources in common use even ten to fifteen years ago, and it was left to each national laboratory to choose its own method for bridging the colour step between the sub-standards maintaining the unit and the working sub-standards used in the photometry of commercial lamps. In this country the method adopted was the so-called "cascade"

*Ces laboratoires sont: le Laboratoire Central d'Electricité à Paris, le National Physical Laboratory à Teddington, et le Bureau of Standards à Washington.

method, in which five additional sets of sub-standards were employed to divide the colour difference into more or less equal steps([5]). Other methods were adopted in the other countries, and, as might perhaps be expected, the results were not quite identical. The agreement was, however, fairly satisfactory, and the following table shows the results of two intercomparisons carried out at different times by means of lamps exchanged between the Bureau of Standards, the L.C.E., and the N.P.L. The figures show the mean ratio of the luminous intensities of sets of lamps operating at a colour temperature of about 2220°K when measured at the three laboratories([4]).

TABLE I.

Laboratory	Mean Relative value of c.p.	
	1912-13	1924-26
Bureau of Standards ...	0.9984	0.9977
Laboratoire Central ...	0.9999	—
National Physical Lab. ...	1.0017	1.0022

(The above figures are based on a mean value of unity in each case.)

Unfortunately, the position with regard to the ratio of the "International Candle" to the Hefnerkerze was much less satisfactory and it soon became clear that there was, in practice, a departure from the accepted ratio of 1/0.90, the amount of this departure increasing with the colour temperature of the lamp measured. The matter had to be dealt with somewhat hurriedly, and at its meeting in 1928 the International Commission on Illumination adopted, as an interim measure, the following values for the ratio([5]):—

Colour Temp.	Approx. Ratio (Int. Candle/Hefnerkerze).
2000°K	1.11
2360°K	1.145
2600°K	1.17

Clearly this agreement could serve only as a stop-gap measure, for it was fundamentally illogical and showed only too plainly the necessity for agreeing upon a method for establishing the unit at any desired colour temperature from the original standards held at the various national laboratories. The theoretical basis for such a method was already in existence in the table of values of the visibility factor, adopted by the I.C.I. in 1924([6]), so that the correct method was one which would give results consistent with these values.

Researches were at once begun in the U.S.A., France, Germany, and Great Britain in order to find out the degree of consistency which could be obtained by the various possible practical methods, and at the meeting of the I.C.I. in 1931 it was reported([7]) that the national laboratories had agreed to adopt the method in which a blue glass was used to bridge the colour difference between the original sub-standards and sub-standards operating at about the same efficiency as the ordinary tungsten filament vacuum lamp. The transmission factor of this blue glass was found by a spectrophotometric determination of its spectral transmission curve, wave-length by wave-length, and computation from the formula

$$\tau = \int \tau_\lambda V_\lambda E_\lambda \, d\lambda \Big/ \int V_\lambda E_\lambda \, d\lambda$$

where $E_\lambda \, d\lambda$ is the energy emitted by the sub-standard in the wave-length interval λ to $(\lambda + d\lambda)$, V_λ is the visibility (luminosity) factor and τ_λ the transmission factor of the glass, both at wave-length λ.

The Bureau International des Poids et Mesures.

While the work mentioned in the preceding paragraph was still in progress the subject of photometric units and standards was taken up by the international body concerned with the primary standards of length and mass. This body, the Comité International des Poids et Mesures, had already begun work on the electrical units and standards, and for this purpose it had set up a Comité Consultatif d'Electricité. In 1929 this advisory committee was asked to include in its terms of reference the photometric units and standards, and it had before it, at its meeting in 1930, a paper from the Bureau of Standards describing a form of primary standard of light([8]). This was a practical realisation of the original proposal, made in 1908 by Waidner and Burgess, to use as standard a specified area of a black-body (Planckian) radiator maintained at the melting point of platinum. The form of black-body proposed has already been described before the Photometric Section of this Society([9]).

The membership of the advisory committee was enlarged by the addition of experts on photometry, and at the first meeting of the reconstituted Comité Consultatif d'Electricité et de Photométrie, which took place in 1933, two important decisions were made, viz. (i) to request all the national laboratories

to determine, in terms of their existing unit, the brightness of the black-body radiator at the temperature of solidification of molten platinum, and (ii) to adopt officially the table of values of the relative visibility (luminosity) factor agreed on by the I.C.I. in 1924([10]).

In 1935 it was decided to form a separate Comité Consultatif de Photométrie, and the personnel of this committee was made more or less identical with that of a special committee on units and standards which had been set up by the International Commission on Illumination in 1931([11]). Thus there was, from the start, the closest possible liaison between the body representative of all those interested in lighting (including the commercial interests) and the body established by international Governmental agreement.

The New Candle.

The new Comité Consultatif de Photométrie met for the first time in 1937, and its principal business was to consider a proposal put forward by the representatives of the national laboratories on the subject of the unit of luminous intensity and the mode of realising this unit at any colour temperature.

Reports received from the Bureau of Standards, from the University of Strasbourg in France, and from the National Physical Laboratory showed that the values found at those laboratories for the brightness of the black-body radiator at the temperature of solidification of platinum (2046°K) were respectively 58.86, 58.78, and 59.0 candles per sq.cm.([12]). The mean value might therefore be taken as 58.9 with an uncertainty of less than 0.2 per cent. The new proposal was to adopt a unit of such a magnitude that the brightness would be exactly 60 of these new units per sq.cm. This would, of course, have the effect of reducing the magnitude of the unit by about 1.8 per cent. at the colour temperature 2046°K, but it was known that the size of the unit at present in use at colour temperatures in the neighbourhood of 2360°K was already too small by something like 1½ per cent., due to the fact that the methods by which the unit at the higher colour temperature had been derived from the unit at the colour temperature of the national standards did not give results consistent with the visibility factors. The change of magnitude proposed for the unit was, therefore, such as would almost cancel the error in the derived unit, so that the combined effect of the adoption of the new unit and of the correct procedure for passing from one colour temperature to another would be very small at colour temperatures in the practically important region about 2360°K, the region including the vacuum lamp.

The proposal to change the magnitude of the unit and to specify the method of passing from one colour temperature to another were embodied in the following resolutions([13]):—

(1) From January 1, 1940, the unit of luminous intensity shall be such that the brightness of a black-body radiator at the temperature of solidification of platinum is 60 units of intensity per square centimetre.

This unit shall be called the " new candle," with appropriate translation into other languages.

(2) (a) The values of the photometric quantities in the case of light sources having a colour other than that of the primary standard shall be determined by a process based on the curve of visibility (luminosity) factors adopted by the Comité International des Poids et Mesures.

(b) To ensure uniformity of procedure among the metrological institutes of different countries when passing from the new primary standard to secondary standards having incandescent filaments operating at higher photometric efficiencies, the method at present adopted is that in which blue filters are inserted between the photometer and one of the light sources to be compared, so as to give a sensation colour match between the two parts of the photometric field.

The new unit adopted in this resolution was to replace both the so-called " International Candle " and the Hefnerkerze, so that there would then be one universally accepted unit of luminous intensity and, consequently, one universal system of units for all the related photometric quantities.

Inter-Comparison of Lamps Measured in Terms of the New Candle.

It was clearly desirable that, before the date proposed for the introduction of the new unit, there should be an inter-comparison of lamps measured at the various national laboratories in terms of this unit, and a second resolution was therefore adopted by the advisory committee as follows([14]):—

The national laboratories are asked to prepare two groups of six lamps, one of the groups operating at the colour temperature of solidification of platinum, the other at the

colour temperature 2360°K, the luminous intensities being measured in terms of the new candle.

It is requested that these lamps be sent before April 1, 1938, to the National Physical Laboratory so that comparisons may be carried out between them.

In accordance with the terms of this resolution, lamps were sent by the other national laboratories to the N.P.L. and their luminous intensities were measured in terms of the new candle as determined at Teddington. From the results thus obtained the relative values of the candle as determined at the different laboratories could be ascertained. The following table shows the value of the unit at each laboratory, taking the mean of all the laboratories as unity(15):—

Table of Relative Values of the New Candle as determined at the Different National Laboratories.

Laboratory	Value of New Candle	
	Colour Temp. 2046° K	Colour Temp. 2360° K
Bureau of Standards ...	0.9990	0.9994
Phys.-Tech. Reichsanstalt	0.9964	0.9931
Lab. Cent. d'Electricité ...	1.0061	0.9972
Electrotech. Lab., Tokyo...	0.9968	1.0084
National Physical Lab. ...	1.0016	1.0018

These results were reported (of course in fuller detail) at a meeting of the Comité Consultatif de Photométrie held in June, 1939, and at that meeting a resolution was passed that the new unit should be introduced during the course of the year 1940.

The Present Position.

The position has unfortunately been complicated by the outbreak of war. The Comité Consultatif de Photométrie is, as its name implies, solely an advisory body without executive powers. Consequently its resolutions have no force unless ratified by the executive body. That body is the Comité International des Poids et Mesures which derives its power from the Conférence générale des Poids et Mesures, the body to which representatives are sent by the governments of most countries. The Comité International was to have met in October, 1939, and it would have received, and no doubt adopted, the resolution of the Comité Consultatif de Photométrie. As, however, the meeting could not be held, this resolution has still only the status of a recommendation. Further, it is evidently essential that any change of this kind should be made simultaneously in all countries, and this is clearly impossible to arrange under present conditions. It has, therefore, been agreed that no action shall be taken for the present on the resolution of the Comité Consultatif, and each laboratory will, therefore, continue to employ the old unit until conditions make it possible to effect the proposed change.

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(A further paper entitled "The Relative Luminosity Curve for the Human Eye and the Standard Photometric Observer," by Mr. J. S. Preston, M.A., A.M.I.E.E., F.Inst.P., F.I.E.S., the presentation of which at the meeting on May 7, was unavoidably postponed, has now been completed. This will appear in the next issue of the "Transactions.")

THE PHYSICAL REALISATION OF THE C.I.E. AVERAGE EYE

By G. T. WINCH, M.I.E.E., F.Inst.P. *(Member)*, and C. F. MACHIN, B.Sc., A.Inst.P. *(Member)*.

(Communication from the Staff of the Research Laboratories of The General Electric Company, Limited, Wembley, England.)

(Read at the Meeting of the Illuminating Engineering Society, on Tuesday, May 7, 1940.)

SUMMARY

After a brief historical survey of attempts at the realisation of a physical eye of defined spectral sensitivity, the earlier methods and technique employed are appraised. Subsequently, the problem is stated, both from the theoretical and practical aspects.

The main treatment of the paper deals with the description of the multi-purpose apparatus which the authors have developed and which is suitable for use as an "average eye," as defined by the Commission Internationale d'Eclairage. It can be adapted for use as a physical colorimeter indicating directly the C.I.E. trichromatic coefficients of coloured light and as an instrument for measuring spectral luminosity distribution in terms of the proportion of the total luminosity in each of 8 defined spectral bands.

Finally, the possible general application to commercial photometry, colorimetry and colour rendering measurements, is discussed.

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(1) Introduction and Problem.

Photometric workers have always had to contend with the difficulties and inaccuracies involved when comparing light sources differing in colour and/or spectral energy distribution. The development of electric discharge lamps, with their application in the lighting field, has stimulated interest in the problems of heterochromatic photometry which consequently arise. Since the beginning of this century the unit of light has been held at the National Laboratories(1) in terms of carbon and tungsten filament lamps which it is intended to supersede by the " new unit of light." The spectral energy distribution and colour of the many forms of electric discharge lamps are so dissimilar from that of these standard light sources that large groups of observers must be employed when making accurate visual comparisons.

Special techniques are necessary because the spectral sensitivities of individual observers' eyes differ widely, and inevitable differences arise in their judgment of the point of photometric balance in the presence of a colour and/or spectral energy difference. The extent of the resulting discrepancies will depend on the colour vision characteristics of the observers, the form and size of the photometric field, the field brightness and the adaptation conditions of the observer when making the measurements(2). The extent of the variations in the spectral sensitivity of individual observers may be gathered from Fig. 1, which shows a number of spectral sensitivity curves obtained by Coblentz and Emerson(3). In 1924 a spectral sensitivity curve, based on the observations

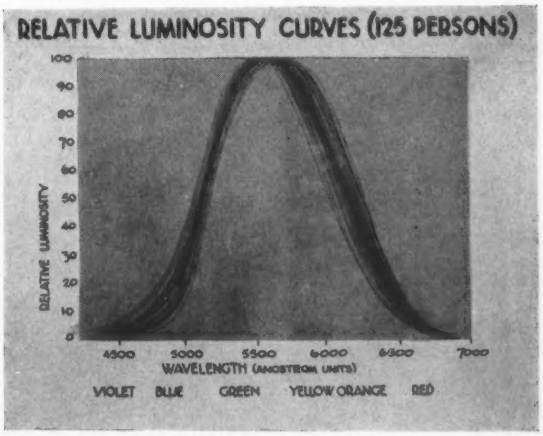


Fig. 1.

of a large number of observers, was adopted by the Commission Internationale d'Eclairage, as representing that of the "average eye." It was further agreed that all heterochromatic comparisons were to be made by methods which gave results in accordance with those which would be obtained by this hypothetical "average eye." This spectral sensitivity curve has since been questioned by more recent investigators(4), but the evidence available at the 1939 meetings of the C.I.E. was not considered sufficiently conclusive to warrant any change being made to the original curve, at least for the present. At the same time it was confirmed that all photometric measurements, whether visual or physical, should be made in terms of the "average eye" so specified.

The realisation of a physical eye having the spectral sensitivity of the average eye has, in consequence, been the aim of many photometric investigators(5) since the beginning of this century, as the construction of such an apparatus would enable light sources of any colour or spectral energy distribution to be photometered in one non-visual observation.

(2) Practical Realisation.

The design of a physical eye apparatus will be influenced somewhat by the choice of physical receiver, the following types of which are available:—

(i) Thermopile.
(ii) Rectifier type photoelectric cell.
(iii) Emission type photoelectric cell.
(iv) Electron multiplier type photoelectric cell.

The great merit of the thermopile is that its spectral response is, or at least should be, uniform throughout the spectrum. Consequently, if it is desired to modify this, the extent of the modification corresponds to the spectral transmission of the filter, or equivalent, used in front of the thermopile. Unfortunately, the sensitivity of thermopiles in the visible spectrum is low in comparison with that of photoelectric cells, and delicate high sensitivity galvanometers must be used to measure the current output, as valve amplification is precluded, because of the low resistance of the device.

Although rectifier type photocells have a very much greater sensitivity to light than thermopiles, namely of the order of 400 micro-amps per lumen, their low resistance again makes valve amplification impracticable.

The output of vacuum emission photocells of the type suitable for this purpose is only of the order of 2 micro-amps per lumen, but amplification is possible. In fact, the photocell and amplifier arrangement used by the authors has an overall effective sensitivity of 20 amps per lumen, or approximately 100,000 times that possible with rectifier cells. Linearity tests on a number of emission cells, of the type used in this work, have shown that their photoelectric current is proportional to the incident light to within about five parts in ten thousand, over an illumination ratio of 10 to 1. The stability is also, in general, better than that of rectifier photocells. Frequency response tests on the emission cells using sector discs indicated that no error is likely to arise in the measurement of discharge lamps operating on A.C. These characteristics make this type of photocell eminently suitable for all types of precision photometric measurements.

The self amplification of the electron multiplier type of photocell at first sight appears very attractive, but the necessity for accurately regulated high voltage excitation may prove an inconvenience.

With the exception of the electron multiplier type, all these physical receivers have been used by earlier investigators in an attempt to construct a physical eye, and the modification of the spectral sensitivity of these receivers to that of an average eye has been attempted by one of the two following methods.

(a) Filter Method.

Colour filters suitably selected, or especially designed, may be used in front of a physical receiver as a means of modifying its spectral sensitivity. Many workers(6) have obtained approximations to average eye spectral sensitivity either by the superposition of a number of commercially available gelatine or glass filters, or by the use of a liquid filter of controlled components and concentrations, in conjunction with a suitable receiver. However, the filter method suffers from the limitations which arise because the spectral response of the receiver must first be accurately measured, or in the case of a thermopile, tests made to ensure that it is a total absorber. Also, the spectral absorption of any optical components and integrator paint to be included in the final photometric "set up" must be determined. From these data and the average eye spectral response data the ideal filter must be calculated, and subsequently fabricated. If, when such filters have been prepared and positioned in the apparatus, a test of overall sensitivity indicates that the required conditions have not been accurately fulfilled, the process of adjustment is likely to prove a long and difficult, if not impossible, task. For these reasons the filter method is unlikely to be suitable for the most precise photometric work in which light sources

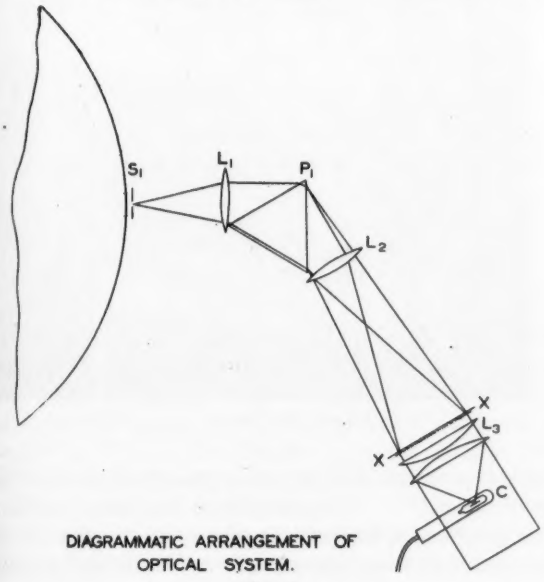
differing widely in spectral energy distribution and colour are to be measured.

(b) THE DISPERSION AND MASK METHOD.

(i) *Historical.*—In the simplest form of this method the light from the source under test is dispersed by a prism, as in a spectrometer, and in the plane of the spectrum image a restricting aperture is arranged in the form of a mask of suitable shape. Subsequently, the light is recombined on to the physical receiver by means of a suitable lens. The contour of the mask is adjusted so that the overall spectral response of the apparatus is the same as that of the average eye.

Pfund first proposed this method in 1906; it was later developed by Strache(7) and in 1911 by Ives and Brady(8), using a thermopile as a receiver. Later, other workers have continued investigations in this field(9).

The earlier attempts have not yielded results of sufficient accuracy when measuring light sources of low lumen value for the developments to have passed the laboratory stage. In fact, the limited sensitivity has restricted the measurements to those of directional candle power. Recently, van Alphen(10), Voogd and Went(11) have described a physical eye of higher sensitivity, employing a condenser discharge method of measuring the photoelectric current. The integral transmission values of colour filters measured with this apparatus are in close agreement with the calculated values derived from spectral transmission data. However, although they claim that the sensitivity allows the apparatus to be used for measuring lumens of lamps operating in a photometric integrator, no results are given.



DIAGRAMMATIC ARRANGEMENT OF OPTICAL SYSTEM.

Fig. 2.

(ii) *General form of apparatus.*—The general form of the apparatus developed by the authors and referred to in the previous section as the mask method, is illustrated diagrammatically in Fig. 2. It consists essentially of a spectrometer whose entrance slit S_1 is illuminated by the test source, either directly or via the window of a photometric integrator. The light is collimated by the lens L_1 dispersed by the Prism P_1, and brought to a focus by the Lens L_2 in the plane XX. In this plane a mask is arranged, which restricts the aperture to the desired extent at those wavelengths where the physical receiver is relatively more sensitive than the C.I.E. average eye. It should be noted that the C.I.E. spectral sensitivity curve(12) is taken to represent the best estimate of the average spectral sensitivity of all observers. However, the apparatus and technique to be described would not need to be substantially modified if subsequently any change were made in the internationally agreed average eye spectral sensitivity curve. Returning to Fig. 2, it will be seen that the light passing the mask is collected by the condenser lens L_3, and an image of the lens L_2 is brought to a focus on the cathode of the photoelectric cell C.

(3) Details and Development of Apparatus—Mask Method.

(a) EXPERIMENTS WITH SMALL APERTURE APPARATUS.

(i) *General arrangement.*—Preliminary experiments were made with a small spectrometer, and the valuable experience thus gained was used in the

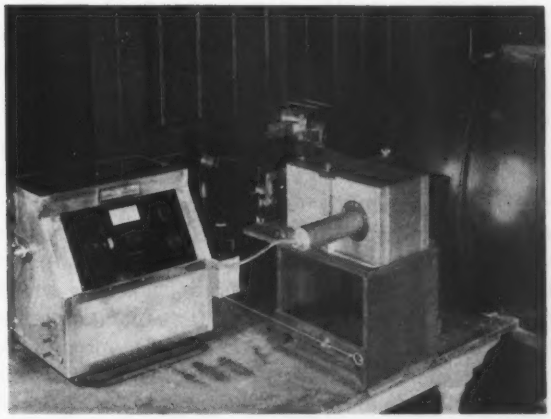


Fig. 3. Small aperture apparatus—shown diagrammatically in Fig. 4.

subsequent design of a large aperture apparatus to be described in a later section of the paper. A photograph of this preliminary apparatus is shown in Fig. 3, and is further illustrated in Fig. 4. It will be seen that the slit of the spectrometer is illuminated, either by the diffusing window in the 2 ft. 6 in. diameter

GENERAL ARRANGEMENT OF SMALL APERTURE APPARATUS SHEWING FACILITIES FOR USING EITHER 6 FT. SIDE CUBICAL, OR 2 FT. 6 INCH DIAM SPHERICAL, INTEGRATOR.

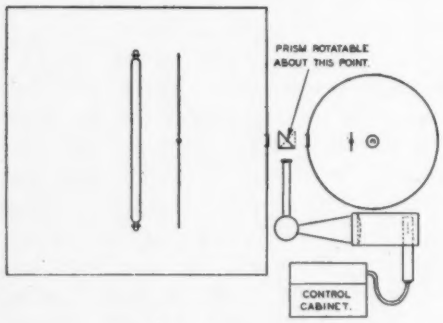


Fig. 4.

spherical photometric integrator, or by a similar window in the side of a cubical integrator of 6 ft. side, depending on the position of the prism. This facility was found useful when making measurements on larger lamps than could be accommodated in the small integrating sphere.

(ii) *Spectrometer.*—The spectrometer used was of the constant deviation type, having a collimator aperture of $f11$. The collimator and telescope lenses were of such focal lengths that a slight magnification of the entrance slit was obtained. The visible spectre was 4 cm. long, and 1.5 cm. high.

(iii) *Development of mask.*—In Fig. 3 the mask can be seen arranged in the spectrum image plane. It is mounted on a detachable carrier located on an existing vertical slide. For convenience, the mask contour was made in two symmetrical halves, as will be seen by reference to the photograph in Fig. 5. The two halves were cut from sheet brass, on an engraving machine, using an enlarged hand-cut template as the pattern, and the two contours which were sweated on to the stiff locating frame were protected at their edges by a glass cover. The assembled mask was examined on a projector of x 50 magnification, and the height of the mask opening was measured at ten positions along its length. This inspection indicated that the maximum departure from the designed dimensions of the contour did not exceed 4/1000 of an inch, the maximum height of the opening being about half an inch. Previous to the adoption of this method, a photographic technique had been tried in which a reduction to the correct size was made from a hand-drawn master. However, efforts to produce a mask image with a sufficiently clear centre portion were unsuccessful, and for this reason this method was abandoned. One experimental mask was made by the British Scientific Instrument Research Association, using a photographic method in which the clear portions were perfectly transparent, and the opaque surround had a bright silver finish. This met the very stringent requirements, but, due to the difficulty of locating the glass slide in the correct position in its holder, the mechanical engraving method already described was preferred.

(iv) *Photoelectric universal photometer.*—It is convenient at this point to give a brief description of the high sensitivity direct reading photoelectric photometer which constituted the receiver on which the emergent light from the spectrometer was recombined. This apparatus was used, both in the preliminary trials and in the larger aperture instrument, to be described later. Considerable experience in this field had been gained by the authors in the development of commercial photoelectric photo-

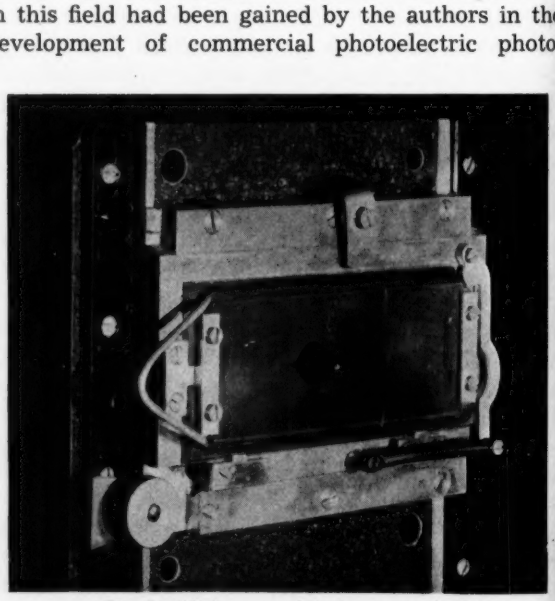
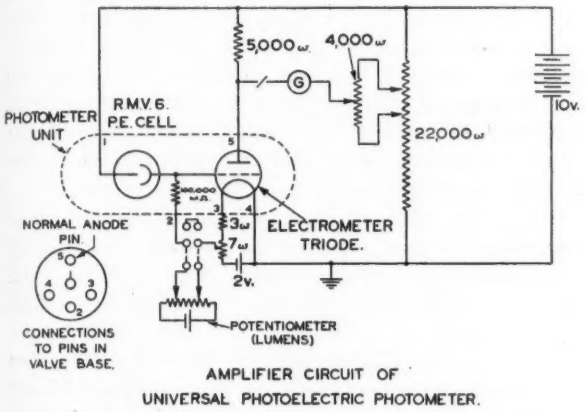


Fig. 5. Mask mounted in locator carrier.

meters prior to 1935, which is described in an earlier publication([13]). This experience was found useful in the design of a photometer of a form suitable for use in any application where high sensitivity and stability are required. This universal photometer, which was

first shown at the Physical Society Exhibition in January, 1937, was found in its most sensitive form to be eminently suitable in the present development. The D.C. valve bridge circuit used is shown in Fig. 6.



AMPLIFIER CIRCUIT OF UNIVERSAL PHOTOELECTRIC PHOTOMETER.

Fig. 6.

The photometer consists of two components, a photometer unit and a control cabinet. The photometer unit takes the form of an evacuated glass bulb, containing a vacuum emission type photocell, an electrometer valve, and a 100,000 megohm grid leak. This form of construction ensures that the high grid insulation is maintained constant independent of atmospheric conditions. A photograph of such a unit, fitted with a grid resistance made up of ten Dubilier 10,000 megohm grid leaks, is shown in Fig 7.

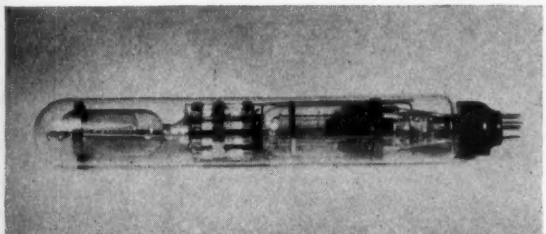


Fig. 7.

The circuit diagram in Fig. 6 shows the components of the photometer unit within the dotted area. The remaining components are adequately screened by the copper casing of the control cabinet indicated on the left in Fig. 3. The copper screened flexible five-way lead connects the photometer unit in its screened housing to this control cabinet.

The method of operating this photometer is to balance the valve bridge with the photocell dark, and the grid potentiometer set to zero. Subsequently, when light falls on the cell, the voltage produced across the grid leak is compensated by an equal voltage applied from the grid potentiometer which is proportional to the incident light. This condition is indicated when the bridge is balanced as shown by no deflection on the galvanometer.

In the present application an R.M.V.6 thin film rubidium vacuum photocell has been used, having a sensitivity of approximately 2 micro-amps per lumen to white light. The stability of the amplifier is such that with a galvanometer having a sensitivity of 480 cm. per micro-amp. and a resistance of 143 ohms, a repetition accuracy of measurement of the order of $\pm$ 0.2 per cent. is possible when the photoelectric current produces 1 volt on the grid. As the photocell cathode area is approximately 1/100 sq. ft., 1 volt will be produced on the grid by an illumination of 0.0005 ft.c., which can therefore be measured to this repetition accuracy of 0.2 per cent.

(v) *Summary of preliminary experiments.*—These preliminary experiments revealed limitations in the apparatus which are summarised below, together with those modifications in design which suggested themselves.

Limitation.	Proposed Modification.
(1) Inaccurate contour and inaccurate location of mask.	Larger mask with variable contour to be adjustable in situ.
(2) Integration errors in the case of sodium lamps when operating in the 2 ft. 6 in. diameter sphere.	Five feet diameter spherical photometer integrator.
(3) Compensation for reduction of light due to large integrator proposed in (2).	Large aperture optical components.
(4) Impurity of spectrum.	(a) Reduction of scatter at optical surfaces by regular polishing. (b) Double spectrometer.

A new experimental instrument has therefore been constructed including these modifications and improvements, and the details of the new design will now be discussed.

(b) Large Aperture Apparatus With Adjustable Mask.

(i) *General arrangement.*—The general arrangement is not different in principle from that already indicated in Fig. 2, but the photograph in Fig. 8 shows the mechanical details. It was soon found that all the components would have to be mounted rigidly on some solid foundation. The entrance slit, collimator lens, and prism, were therefore mounted on a small platform of robust construction, which was bolted to a cast-iron bed of generous proportions. The telescope

lens, mask, collecting condenser and photoelectric cell were mounted as another unit on a baseboard which could rotate about a point beneath the prism, and which, when correctly positioned, could be rigidly clamped to the cast-iron bed. This arrangement was found to give the desired mechanical stiffness to ensure the stability of wavelength calibration which is required for a constant overall spectral sensitivity.

Fig. 8. General layout of large aperture apparatus.

Because of the large range of light intensities to be measured, various sector discs were used between the window of the integrating sphere and the entrance slit.

(ii) *Spectrometer.*—It was decided to provide a curved entrance slit which could be varied in width (see Fig. 9). The curvature was experimentally determined to produce a straight image of the mercury green line (0.5461μ). In this work the entrance slit was set to a width of 0.22 mm., almost giving resolution of the yellow mercury doublet. The collimator lens, a Dallmeyer Pentac, having a focal length of 5 in., has an aperture of f 2.9. The 60 degree prism has a 3-inch side and is of dense flint glass of refractive index 1.75. The telescope lens L_2 is a Petzval objective of 30-inch focal length, and gives a magnification of the entrance slit of approximately 6 to 1, producing a spectrum 10 cm. high and 10 cm. long between the visible wavelength limits of 0.4 and 0.7μ. With a spectrum image of this size, a mask with an adjustable contour becomes practicable. The plano-convex condenser pair of 8 inches diameter and 6 inches focal length, is used to recombine the spectrum on to the cathode of the photocell.

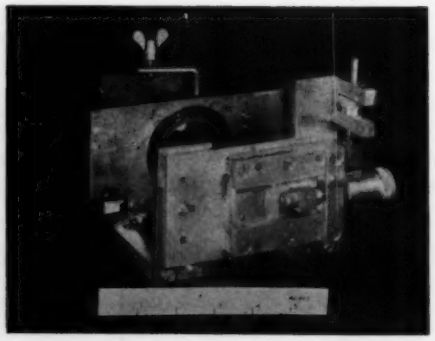


Fig. 9. Curved entrance slit, collimating lens and prism.

Successive calibrations of this arrangement over the first two weeks it was in use showed no change in wavelength calibration greater than 0.0005μ, and there is no indication so far that changes greater than this will occur.

(iii) *Variable contour mask.*—After one or two experimental forms of construction of mask had been investigated the arrangement indicated in the photograph in Fig. 10 was adopted. The masking is performed, in the main, by a template of approximately the correct shape. The final adjustment of the shape is made *in situ* by the movement of a series of leaves,

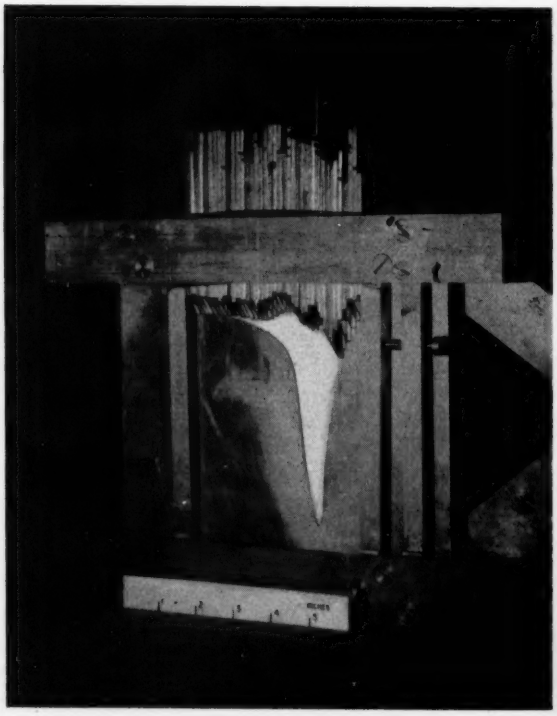


Fig. 10. Frame carrying fixed template and adjustable leaves along top edge.

the ends of which form the top boundary of the aperture, as illustrated in Figs. 10 and 12. The leaves are made of channel section brass, of ½-inch channel

EFFECT OF COMPLETE VARIABLE CONTOUR WITHOUT PRINCIPAL TEMPLATE.

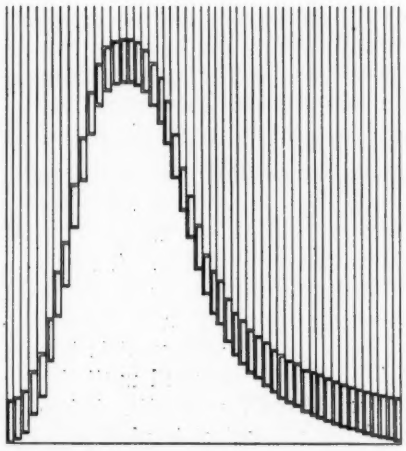


Fig. 11.

width, with ⅛-inch sides, some of which were machined down to 1/16-inch, to provide smaller steps for the more critical parts of the contour. The leaves are clamped between two brass guides, with

PRINCIPAL TEMPLATE WITH VERTICALLY SLIDING LEAVES FOR FINE ADJUSTMENT OF CONTOUR.

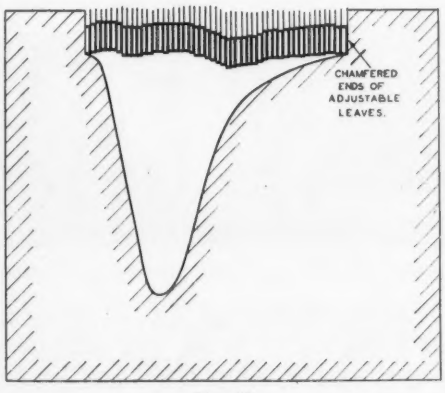


Fig. 12.

a rubber friction pad interposed on one side, as indicated in Figs. 10 and 13. The channel section was chosen to limit the frictional area of contact between adjacent leaves whilst providing a relatively large frictional surface to the side friction pad. This allows of the adjustment of an individual leaf without disturbing the one next to it. The function of the fixed approximate contour is illustrated by reference to Figs. 11 and 12. Had the arrangement in Fig. 11 been adopted the extremely "stepped" nature of the contour would probably have given rise to large errors in the measurement of certain monochromatic sources.

It may be useful here to draw attention to the order of mechanical accuracy required in the contour of a mask, considered from the point of view of the theoretical requirements, particularly when photometering electric discharge lamps. The requirements are most stringent in the case of the

ARRANGEMENT OF CHANNEL SECTION TO FORM VARIABLE CONTOUR.

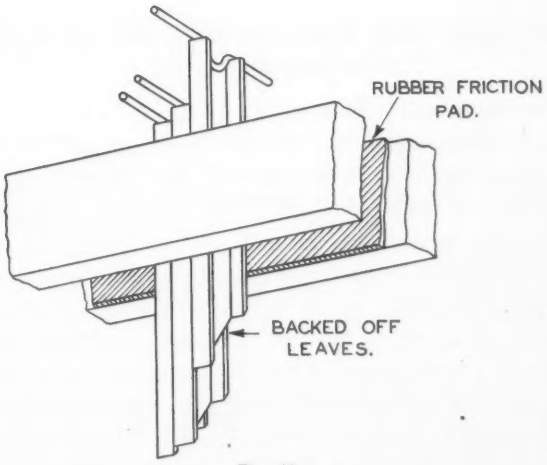


Fig. 13.

sodium lamp as over 99 per cent. of the radiation is in the D line, at wavelength 0.5896 μ. It follows, therefore, that the height of the mask at this wavelength must be correct to the percentage accuracy to which the lumens of the lamp are to be measured, assuming, of course, that the rest of the mask is sensibly correct. If this photometric accuracy is to be 1 per cent. in an instrument of unity magnification, such as that used in the earlier experiments, section 3 (a) (i), in which a fixed mask was employed, the height of the mask at this wavelength was only 1.05 cm., so that this needed to be correct to within 0.01 cm.

In order to obtain a wider mask aperture at the ends of the spectrum König and Voogd[14] have

used a colour filter in their apparatus which gives an approximate correction to average eye sensitivity, the mask being used only for the fine adjustment of the spectral response to compensate for the shortcomings of the filter. In the author's experience the work involved in measuring the overall sensitivity of the apparatus, calculating and making a filter for this purpose, is hardly justified unless, perhaps, in the case where stable filters, made to special design, are readily available. The fixed template method was considered simpler as the shape can be deduced by a preliminary adjustment of the leaves, as shown in Fig. 11. The shape of the contour formed by this method has in its fixed form to be inverted when the leaves are used for fine adjustment only. However, the symmetrical intensity distribution along the spectral lines from top to bottom results in a negligible distortion of the contour, which, in any case, is within the range of the adjustable leaves.

(4) Initial Tests, Adjustment and Calibration of New Experimental Apparatus.

(a) Preliminary Tests.

(i) *Stray light.*—In the initial adjustment of the apparatus, tests were made of the impurity of the spectrum, impurity in this case implying misplaced spectral light. This impurity may be present in two forms, either as scatter produced by scratches on the optical surfaces, or by specular reflection from the rims of lenses or screens. The general scatter produces a background of light of the colour under test, whilst the specular reflections give rise to misplaced subsidiary spectra. After all the optical surfaces had been cleaned, a general test was made for the magnitude of the stray light present, by isolating with an exploring slit a small section of the mercury spectrum including the green 0.5461μ line, and investigating the purity of the line with colour filters.

An amber filter of 0.5 per cent. transmission to the green line was interposed in the optical system. The light emergent from the exit slit at this stage was composed of about 0.5 per cent. of the green line, together with any stray light present. This stray arose mostly in this case from the yellow line which was freely transmitted by the amber filter. A further filter comprising a yellow gelatine between two didymium glasses was inserted in the optical path. This filter, which has a high transmission to the small quantity of the emergent green light, eliminates almost entirely the yellow stray. From measurements of the emergent light before and after the insertion of the latter filter a fair estimation of the stray light can be made. The principle of this method was also applied to the yellow mercury line and to various wavelengths of the continuous spectrum from a tungsten filament lamp.

As all these tests indicated that the percentage impurity at any wavelength was only of the order of 0.3 per cent., this result was considered satisfactory at the present stage of the development. Should a higher purity subsequently be found necessary, it is proposed to use a double dispersion instrument.

(ii) *Measurement of dispersion of the prism.*—The dispersion was determined by exploring the spectrum image with a detachable exit slit, carried on the same framework as that in which the adjustable mask is located (see Fig. 14). A vernier scale is attached to the exploring slit to indicate its position.

A cadmium-mercury and a sodium lamp were operated together in the photometric integrator and the exploring slit was adjusted until the maximum light was transmitted by the slit. When this was indicated by the photoelectric photometer reading, the vernier scale indicated the relative position of the spectral line. This operation was repeated in turn for all the spectral lines, and in Fig. 15 slit position is shown plotted against wavelength. For accurate extrapolation to the two extremes of the visible spectrum the values of slit position for three wavelengths were substituted in the formula.

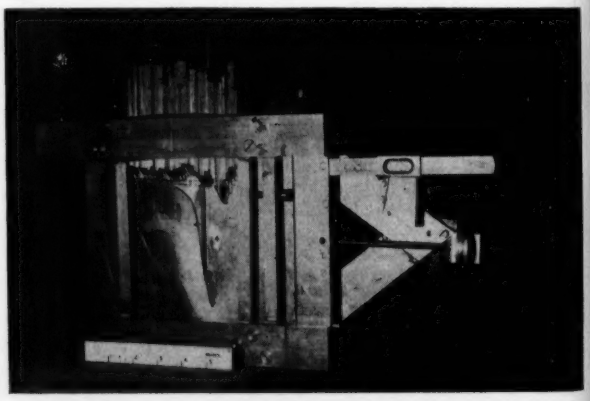


Fig. 14. Adjustable mask with exploring slit in position.

$$D = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where D is the vernier scale reading corresponding to wavelength λ, and A, B, C are constants. The calculated position of the other five lines was found

to agree with the measured values to within the accuracy of reading the vernier scale. The exploring slit used in the present calibration and which it was proposed later to use in the exploration of an illuminant of known spectral distribution was of 1.5 mms. width. The slope of the calibration curve obtained by differentiation of equation (1) gives to a close approximation the wavelength range embraced by this slit at any particular wavelength setting.

(b) ADJUSTMENT OF MASK CONTOUR.

(i) *Source of radiation of known spectral distribution.*—The colour temperature of a tungsten filament lamp is by definition the temperature of a black body radiator which colour matches the filament lamp. This definition implies that a tungsten lamp is a grey body and will have in the visible spectrum the same spectral energy distribution as that of a black body of the same colour temperature. The data on black body radiators computed by Skogland([15]) were therefore used to define the radiation properties of the tungsten lamps employed in setting the mask contour. These radiation data, in conjunction with the C.I.E. average eye spectral sensitivity data and the differential of equation (1), were used to estimate the luminosity of the energy radiated by the tungsten lamp in the narrow waveband transmitted by the exploring slit. If the overall spectral sensitivity of the apparatus is to be that of the average eye, the photometric readings of light emergent from the exploring slit must be proportionate to this luminosity data at every wavelength.

In the experimental procedure adopted a 2 kw tungsten filament lamp was operated at a colour temperature of 3120 degrees K., in the photometric integrator, and used as the source of known spectral energy distribution in making the following measurements.

(ii) *Preliminary estimation of mask contour.*—The exploring slit was first set at the wavelength at which the luminosity of radiation emerging from the exploring slit was a maximum, and the photometer reading was observed. A ratio (S_λ/L_λ)max. was obtained, where S_λ and L_λ were respectively the photoelectric photometer reading and the corresponding luminosity value at the wave-length λ at which L_λ was a maximum. If the apparatus is to have average eye spectral sensitivity, it follows that the ratio (S_λ/L_λ) must be constant at all wavelength settings of the exit slit. The particular ratio (S_λ/L_λ)max. obtained at L_λ max. was used as a convenient reference point to check the constancy of the sensitivity of the apparatus throughout the period of investigation of other wave-lengths. The slit was traversed across the spectrum and set in turn at positions centrally located with respect to each adjustable leaf of the mask. At each of these positions the leaves were adjusted until $(S_\lambda/L_\lambda) = (S_\lambda/L_\lambda)$max. In this way the preliminary "step" contour, already referred to in Fig. 11, was generated A fixed template was then made to this average form.

(iii) *Final setting of the mask.*—The fixed template was set in the correct position with respect to wave-length, and inverted with respect to the adjustable leaves which were withdrawn to the top edge. The general procedure already outlined in (ii) above was repeated, thus providing the necessary fine adjustment and correction for any slight mechanical imperfection of the contour of the fixed template.

It is clear that at any time a check of the spectral sensitivity of the apparatus can readily be made, and experience has shown that this test can be made in about an hour.

Should the changes of the spectral reflectivity of the integrator paint and any change with time of the photocell spectral sensitivity prove a source of error, adjustment for these changes can readily be made by a resetting of the adjustable leaves.

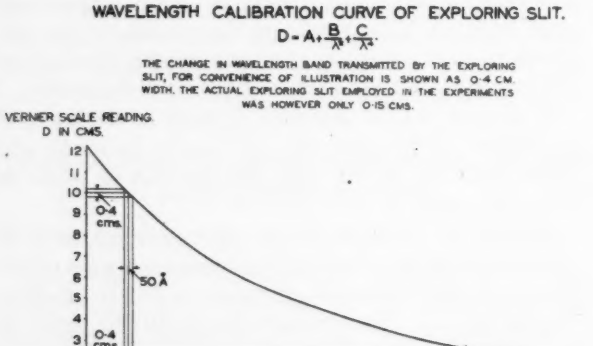
Further, in the event of the spectral sensitivity data for the average eye being changed by international agreement, this can also be compensated for in a similar manner.

(iv) *Calibration for lumen measurement.*—Having completed the procedure outlined above the exploring slit is withdrawn. It follows that the overall spectral sensitivity of the apparatus is now that of the C.I.E. average eye, and can, therefore, be used for measuring the lumens of light sources of all forms of spectral energy distribution when operated in a photometric integrator. The photometer is calibrated by reference to a series of tungsten filament lamps of known lumen values. These are operated in turn in the integrator, and from the respective readings of the potentiometer of the photoelectric photometer an instrument constant is obtained. Alternatively, by using a variable aperture sector disc between the integrator window and the entrance slit, or altering the total voltage across the grid potentiometer of the photoelectric photometer, the instrument can be made direct reading.

It may be of interest here to note that the overall sensitivity of this photometer is such that a 100-lumen

lamp can be measured in a 5-ft. diameter spherical photometric integrator to a repetition accuracy of ± 1 per cent. This means that a lamp of 25 lumens could be measured to the same accuracy when operating in a 2 ft. 6 in. diameter integrator. The integrator window brightness under these conditions is 2.7 candles per square foot, as compared with 13 c.sq. ft. necessary in Voogd's apparatus, in which he was using a collimating lens of f 6.8 and an entrance slit of 0.3 mm. In the present apparatus, it will be remembered, a lens of f 2.9 and an entrance slit width of 0.22 mm. is used.

(v) *Measurement of integral transmission of colour filters.*—It has been stressed throughout the paper that the merit of the method is its pure substitution nature, and, therefore, if it is required to measure the integral transmission of colour filters, some modifications to the apparatus are necessary. It is essential that the insertion of the filter in the optical system should not in any way alter, by disturbance of the optical paths, the conditions under which the photometer was calibrated for spectral sensitivity. Therefore, the filter must be inserted on the side of the diffusing window remote from the entrance slit. In most applications, including that of visual photometry, the light to be transmitted passes normally through the filter, and all measurements, therefore, should be made under these conditions. The physical eye photometer must, in consequence, be calibrated for spectral sensitivity with parallel light normally incident on the diffusing window which illuminates the entrance slit. This arrangement enables the filter to be tested under the conditions in which it is used in photometry, and its insertion in front of the diffusing window will not disturb the calibration conditions.


WAVELENGTH CALIBRATION CURVE OF EXPLORING SLIT.
$D = A + \frac{B}{\lambda} + \frac{C}{\lambda^2}$.
THE CHANGE IN WAVELENGTH BAND TRANSMITTED BY THE EXPLORING SLIT, FOR CONVENIENCE OF ILLUSTRATION IS SHOWN AS 0·4 CM. WIDTH. THE ACTUAL EXPLORING SLIT EMPLOYED IN THE EXPERIMENTS WAS HOWEVER ONLY 0·15 CMS.
VERNIER SCALE READING D IN CMS.
0·4 cms.
50 Å
0·4 cms.
260 Å
WAVELENGTH λ IN μ

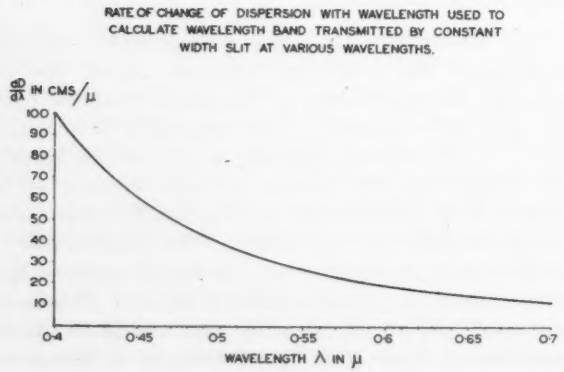

RATE OF CHANGE OF DISPERSION WITH WAVELENGTH USED TO CALCULATE WAVELENGTH BAND TRANSMITTED BY CONSTANT WIDTH SLIT AT VARIOUS WAVELENGTHS.
$\frac{d\lambda}{dD}$ IN CMS/μ
WAVELENGTH λ IN μ

Fig. 15.

(5) Results.

As this experimental apparatus has only very recently been completed, there has not been time to carry out all the exploratory photometric measurements which it is intended to make.

The preliminary results are given in Table 2, which contains the mean lumen values obtained by the visual and physical photometric methods.

Table 2

No. of lamps	Type	Average Lumens		% difference Physical from Visual
		Visual	Physical	
(1)	(2)	(3)	(4)	(5)
2	400w H.P. Mercury	17,100	16,430	— 3.9%
2	250w ,,	7,610	7,390	— 2.9%
2	400w H.P. Mercury Fluorescent	14,600	14,280	— 2.2%
2	25w L.P. Mercury Fluorescent	650	660	+ 1.6%
2	100w Sodium	3,540	3,360	— 5.1%
2	400w Neon	3,250	3,090	— 5.0%

The visual photometric measurements are the means of observations made on two occasions in a photometric standardising laboratory. A group of observers was chosen whose average Y/B was unity, and the measurements were made by the 2 degree field high brightness minimum colour difference method. The results given are the mean of all observers' measurements. The colour filters used in front of the tungsten comparison lamp were measured on a photoelectric spectro photometer, and the integral transmission was calculated from the spectral transmission values and the C.I.E. average eye spectral sensitivity data. In both the visual and physical measurements, the lamps were operated

in integrators of similar size and form, and the electrical measurements made with the same instruments. The same tungsten filament standard lamps were used for calibration in both cases. These precautions were taken to ensure that the photometric conditions were as nearly as possible identical, and to eliminate the chance of operating conditions influencing the results.

These provisional results are of interest, in view of the recent discussions on the average eye spectral sensitivity data. It should also be noted that the differences shown between the visual and physical methods are of the same order as the limits of accuracy quoted by the National Physical Laboratory with respect to their measurements on these classes of lamps.

Measurements of the integral transmission values of a series of colour filters are in hand, and the comparison of these results with the values calculated from the spectral transmission measurements will provide a direct check of the accuracy of the physical eye.

(6) Other Applications.

The practical realisation of a robust direct reading physical eye of high sensitivity which can be readily and accurately adjusted to have any desired spectral sensitivity, provides a convenient solution to other kindred problems, such as the measurement of spectral luminosity distribution and colour.

(a) Measurement of Luminosity in Special Bands.

During the past three years, in parallel with the development of the physical eye, the authors have been concerned with the determination of the colour rendering properties of coloured light sources, particularly in the case of light from electric discharge lamps of the fluorescent type. This problem has also been under investigation in the laboratories of The British Thomson-Houston Company, Ltd., Philips Lamps, Ltd., and Siemens Electric Lamps and Supplies, Ltd., with whom the authors have been privileged to co-operate throughout the course of experiments in which each laboratory has developed independently apparatus for measuring the luminosity of the light from sources under test in eight agreed spectral bands. These luminosity values have been expressed as a percentage of the total luminosity and the results used as a means of indicating the approximate spectral luminosity distribution of the light sources. These measurements provide a useful method of controlling the colour rendering properties of the sources, i.e., the appearance of various pigments when viewed by the light from these sources. For this purpose the authors have, up to the present, used the small aperture physical eye described in Section (3a), with additional masks to isolate the various spectral bands. These masks, which are shown in Fig. 16, were made in a similar manner to the average eye spectral sensitivity mask, and were mounted in similar locating holders. By this means with the lamp under test operating in the appropriate photometric integrator (see Fig. 3) the luminosity in each spectral band is measured in turn through each of the eight masks which are quickly interchangeable, and locate accurately in position.

The eight spectral bands in which the measurements are made and which have been provisionally standardised by the lamp manufacturers in this country and in Holland are given in the following table:—

Band No.	Wavelength		Mask enlargement factor.
1.	0.40μ to	0.42μ	100
2.	0.42	0.44	40
3.	0.44	0.46	20
4.	0.46	0.51	1
5.	0.51	0.56	1
6.	0.56	0.61	1
7.	0.61	0.66	1
8.	0.66	0.72	1

As will be gathered from the aperture of the average eye mask in Fig. 16, at the ends of the spectrum the luminosity values will be small and therefore difficult to measure accurately. However, as these values are required as a control of the colour rendering properties of light sources, although small, they are very important, because the chromaticity value of the light, particularly at the blue end of the spectrum, is very high. In order, therefore, to improve the accuracy to which the low luminosity bands could be measured, their contours were increased in height by convenient multiples. The actual bands affected and the enlargement factors are included in the table above. The photograph in Fig. 16 shows the average eye mask and the eight spectral band masks, together with one having parallel sides. This latter was used for making quick reference to the sodium line in the initial stages of positioning the mask carrier.

As with the measurements of lumens of coloured light sources on this small aperture apparatus, the accuracy of the measurements of luminosity in these defined spectral bands leaves much to be desired. It is, however, expected that the application to the

spectral band measurements of the form of apparatus and technique adopted in the large aperture physical eye, with its accurately adjustable contour mask, should enable considerably improved accuracy to be obtained.

(b) Direct Physical Colorimetry.

The promising preliminary results obtained with the new physical eye method would seem to indicate that it could be utilised to improve the accuracy of the direct reading physical colorimeter indicating on the C.I.E. trichromatic system, described earlier by one of the authors(16). The "average eye" spectral sensitivity corresponds to the $\bar{y}$ distribution coefficient curve and the same technique could be

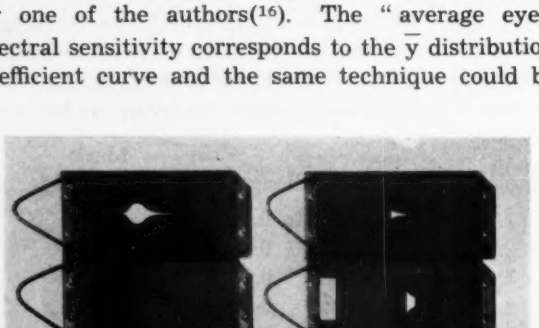


Fig. 16.

adopted to obtain spectral sensitivities corresponding accurately to the $\bar{x}$ and $\bar{z}$ distribution coefficient curves.

(7) Summary and Conclusions.

The new experimental physical eye photometer is shown to be of higher sensitivity than other forms described by earlier investigators.

Any individual photoelectric cell having stable characteristics and a spectral response extending over the whole of the visual range can be used as the receiver in this arrangement, without prior knowledge of its spectral sensitivity.

The adjustment of the spectral sensitivity to that of the average eye is relatively simple, and can be readily rechecked from time to time. Should readjustment be necessary due to changes in the spectral reflection properties of the integrator paint or the spectral sensitivity of the photocell, these can be easily accommodated.

The provisional lumen measurements made with this apparatus on light sources differing widely in spectral energy distribution, indicate that a single measurement will give results comparable in accuracy with those obtained by lengthy and laborious visual methods employing large groups of skilled observers.

It is hoped that data will shortly be available indicating the suitability of this general form of apparatus in applications such as the measurement of the integral transmission of colour filters, spectral luminosity distribution, and colorimetry.

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DISCUSSION

Mr. G. H. WILSON said it had been a joy to him, and no doubt to others, to be transported, as it were, for one and a half hours to the laboratories of the world which had been tackling this problem of the unit of light and other fundamental problems connected with photometric measurements. When he added up columns of £ s. d., as he sometimes had to, he always longed for a decimal system of coinage, but, as they all knew, there was now little consideration given to such proposals because of the difficulties there would be in changing over. Dr. Walsh had suddenly announced that evening that the unit of light was to be changed, and Mr. Wilson said he regarded it as fortunate and a tribute to international co-operation that it had been possible to have a new standard of light like this without all the objections he was sure would have been found in many other matters.

Although the paper by Dr. Walsh was short, it represented many years' work by very many men throughout the world. There was a tendency to take things so much for granted. One measured a lamp and said it had an intensity of so many candles, but one forgot the background behind such a measurement. Therefore, he felt they would not be properly educated as illuminating engineers if they did not hear something about the new unit of light.

Dr. Walsh had passed very quickly over the effect of this change on the candle-power values we had at the moment, but he would like to know the sort of percentage change that would have to be made when the new unit of light was adopted. He himself had a great many Tables which he would hate to have to correct by any large percentage.

Mr. Preston's excellent introduction to the second part of the work seemed to go almost one stage beyond the paper by Messrs. Winch and Machin, and had raised a big difficulty. A month ago Dr. Harper, in that room, showed that with fluorescent powders the square law was obeyed, but Mr. Preston had shown that evening that the square law was not obeyed, the reason being that Mr. Preston's demonstration was at a low level of brightness. Mr. Winch had shown how one could realise the average eye of the I.C.I., but that meant that the results would be applicable only at levels where we knew something about the average eye. When, however, we came down to the low levels of brightness dealt with by Mr. Preston the methods of measurement proposed by Messrs. Winch and Machin would be invalid. He rather felt that Mr. Winch had been a little misleading in the photographs of the apparatus. He himself had been fortunate enough to see that apparatus when it was getting its very finest results. As it had been shown that evening, however, it had been cleaned up, and nobody could see the Plasticine and string which existed originally. In its working state he had felt it to be a true piece of research apparatus where an improvised weight was made by filling a Morris "8" piston with screws and a cup of stale tea seemed to play its part.

Continuing, Mr. Wilson said he wondered what would be the impact of the subject which Messrs. Winch and Machin had discussed on the lighting engineer. It seemed that the human eye was no longer required, and that standardisation in the future might be done with the aid of this hypothetical average eye. How was this likely to affect photometry? Many of them were using more and more photoelectric cells for taking their measurements, and one could hope, he imagined, that eventually an ordinary portable photometer could be devised which would have a sensitivity equal to that of the average eye. When it came to the human eye, however, they had seen from the curve of relative luminosity that eyes varied considerably, and in making measurements of highly coloured sources very large errors were to be expected unless precautions were taken. Therefore, he would like Mr. Winch to give a forecast of the future and to say whether he thought we should continue to use our eyes for photometric measurements or would rely on electrical methods.

Dr. C. C. PATERSON said that in listening to the very clear review of this subject by Dr. Walsh he could not help being impressed with the fact that the people who thought about programmes of work on units and standards did so rather in terms of centuries than years. This had the unfortunate aspect that when a war occurred everything had to begin again afterwards, and all depended on whether an agreement could be scrambled in between wars. He was very much afraid, after this war, of what would happen to the new unit and the prospective agreement which it was hoped to secure from the Germans. However, we must hope for the best, and perhaps Dr. Walsh and himself in 2040 would look down from above, or up from below, and see the Society discussing the finality of this arrangement. He hoped that it would be possible to do something to materialise this unit and get it agreed. As in the case of the so-called International Unit agreed before the last war, when we did not have to change the actual value of our unit, so, in the present case, it

appeared that in England we should not have to change appreciably the practical magnitude of our unit as used in industry.

Mr. M. G. BENNETT congratulated the authors on porducing in material form the hypothetical "standard eye" that we had been talking about for years. What a lot of trouble would have been saved if it had been true, as was stated in "1066 and All That," that the Act of Uniformity said that all men must be the same! To represent the average human eye fully, the apparatus would have to go further than it does and record what the eye sees when it looks out of the corner of the eye as well as when it looks directly at an object, and what it sees at low levels of brightness. The apparatus should put an end to a great deal of discussion and make it possible to get home earlier from meetings of the Society in consequence, because a whole lot of bones of contention would disappear! The authors therefore deserved gratitude even if that were the only thing that came out of this work, but many other good things would also come out of it.

Dr. J. W. T. WALSH, referring to the calibration of the instrument described by Mr. Winch, said he understood that a tungsten lamp was used, and that the spectral distribution was taken as that of a black body at the colour temperature of the filament. He might be mentioning something which was not important, but he believed that the emission from a tungsten filament was never exactly the same as that of a black body at any temperature whatever. He did not know whether the differences were sufficient for them to have to be taken into account. If so, no doubt Mr. Winch had allowed for them, but the impression he had gained was that the spectral distribution from the tungsten filament lamp had been assumed to be the same throughout the spectrum as that of the black body at the colour temperature of the lamp.

Mr. J. S. PRESTON, taking up the same point, said he believed that in a number of determinations of luminosity curves people had assumed what Dr. Walsh had stated, and how far it had led them astray he did not know.

Continuing, he asked Mr. Winch with regard to the portability of the apparatus he had described and about his slightly disparaging remarks with reference to the colour filter method of correcting photoelectric cells to the standard curve. In one of the slides he himself had shown it would be seen that a definite degree of realisation was obtainable, and the amount of that realisation, once one knew the spectral sensitivity of the cell, could be determined by a calculation taking only a few hours, since the transmissions of chemical hues in these filters obeyed well-known laws with regard to density and concentration. One could obtain a very good realisation of the standard eye in that way, and the results, in his view, agreed satisfactorily with the visual results for coloured light sources in present use.

Mr. J. M. WALDRAM suggested that Mr. Winch's apparatus, from its very form, drew attention to the nature of the quantities with which the photometrist and the illuminating engineer had to deal. Illuminating engineering had the disadvantage that it had grown out of photometry, and some of its fundamental ideas had suffered thereby. Photometry was concerned to know when two objects appeared to be of the same brightness; illuminating engineering was mainly concerned with the degree to which objects appeared of different brightnesses. Since the quantities used in illuminating engineering could only be measured by photometry, there was a temptation to use photometric units for purposes for which they could not legitimately be used.

The nature of Mr. Winch's apparatus demonstrated that the conventional photometric units were a compromise between purely physical units and "sensation" units. Illuminating engineering involved both physical and "sensation" phenomena; for example, physical energy supplied to a lamp was transformed to physical radiation at various frequencies which, after reflection at surfaces which varied its properties, reached the eye and resulted in sensation. It would have been consistent—but very inconvenient—if we had invented a purely physical system of units, based upon the amount of energy radiated at various frequencies without reference to the sensation which would be produced, and leaving that sensation to be derived separately. What had been actually done was to invent units which were partly physical and partly took into account some of the sensation effects by weighting the energy at various frequencies in accordance with the agreed standard luminosity curve. In Mr. Winch's apparatus, for the first time, we could see this weighting being performed; and attention was drawn by it to the importance of this luminosity curve and the limited conditions under which it was valid. Recent developments of illuminating engineering had involved very low brightnesses and considerable variations of colour, and had entered regions in which the conventional units were

not always valid, because the luminosity curve is not constant.

Dr. J. W. T. WALSH, in a short reply, said that Mr. Wilson had asked a very awkward question to which he did not intend to give a definite reply. However, he would give a hint. Mr. Wilson did not want to have to change his Tables, and enquired how much his figures would probably have to be altered. Approximately, it could be said that the difference would not exceed ½ per cent. in the 2360° region, and 2 to 3 per cent. at the colour temperatures of gas-filled lamps. For the time being, the name of the new unit was "The New Candle," but it was hoped that in time the names "International Candle" and "Hefner Candle" would drop out and that there would be only one unit, viz., "The Candle." In conclusion he would like to point out to Mr. Wilson that, far from announcing that the unit of light had been changed, he had definitely stated that no change could be made under present conditions.

Mr. G. T. WINCH made the final reply to the discussion. Commenting on Mr. Wilson's remarks that the response of the physical eye would be independent of the illumination level, he confirmed that this was the case, providing, of course, that the leaves of the adjustable mask and therefore the spectral sensitivity of the apparatus were not disturbed. The authors were primarily concerned with the development of a photoelectric photometer having the spectral response of the C.I.E. "average eye," in order to be able to make measurements in terms of average foveal vision, so defined. As Mr. Preston had remarked, the results obtained by the physical eye when set to the C.I.E. "average eye" spectral sensitivity will be quite different from average visual photometric determinations at very low brightness levels using a large field of view, because the spectra sensitivity of the eye under these latter conditions is quite different from that under which the C.I.E. data were obtained, namely, with a small photometric field at high field brightnesses. However, as is stressed in the paper, with the apparatus described, the spectral sensitivity can be set to any desired form of curve, so that if the spectral sensitivity of the average eye at low brightnesses under large field size conditions were available the physical eye could be set up to make measurements in terms of average visual observations under these conditions.

Mr. Wilson had also asked what prospect there was of extending the development of this form of apparatus to portable photoelectric photometers. Mr. Winch admitted that the method was unlikely to be adaptable to portable types of photometer, and that the filter method of modifying the spectral sensitivity was at present the only practicable method in portable instruments. Personally, he thought that the immediate sphere of usefulness of the physical eye was in speeding up the rate at which accurate heterochromatic photometric measurements could be made in the standardising laboratory. Using visual methods to standardise one or two coloured light sources often involved a week's work for a group of skilled photometric observers, whereas with the new apparatus such measurements would be able to be made in a matter of a few minutes. As to the forecast for the future, for which Mr. Wilson had asked, Mr. Winch said he felt confident that in due course this type of apparatus would be incorporated in commercial photoelectric photometers in the works and laboratory with which he was associated.

Mr. Bennett suggested that the apparatus could not be considered to represent the average human eye fully unless it could record what the eye sees by parafoveal as well as by foveal vision. As has already been mentioned in the reply to Mr. Wilson, there is no difficulty in adjusting the apparatus to any required spectral sensitivity; the problem is rather to know or determine to sufficient accuracy the spectral sensitivity of the eye under the various conditions which it is required to simulate by means of the physical eye. With these data available the apparatus can be suitably adjusted to carry out the required measurements.

Dr. Walsh questioned the correctness of the assumption that the spectral distribution from a tungsten filament was the same as that of a black body. The authors had not overlooked this point and their assumption that the tungsten source radiated as a grey body, and in consequence had the same energy distribution in the visible spectrum within the accuracy of measurement as a black body at the same colour temperature, was confirmed by work published by Barnes and Forsythe (ref. 15).

Consequently it was not felt that this assumption would introduce appreciable errors in measurement, and this was confirmed by Mr. Preston's remarks.

Mr. Preston had expressed his disagreement with the authors' disparaging remarks on the use of filters for modifying the photocell sensitivity, but it was pointed out that in the text of the paper (section 2a), it was only stated that the filter method is unlikely to be suitable for *the most precise* photometric work. The authors did not question its usefulness in applications where slightly less accuracy was required and

where the measurement of the spectral sensitivity of the photocell and the preparation of filters presented no difficulties.

The portability of the apparatus had also been referred to by Mr. Waldram, but the authors had not designed this apparatus to be portable, and it was very doubtful whether future editions could be made portable, as apart from transportable. The intention was that such apparatus should be available in photometric standards, or colorimetric laboratories to enable rapid measurements to be made in accordance with the C.I.E. average eye so that lamps could be quickly standardised, or portable photometers calibrated. Mr. Winch could not see eye to eye with Mr. Waldram in his suggestion that light measurements should be made in watts; it was one of those matters in which it would be difficult to change conventional practice, although doubtless Mr. Waldram's suggestion had a much more fundamental basis.

On the motion of the President, thanks were expressed to the Electric Lamp Manufacturers' Association for the use of the Lighting Service Bureau premises, and also to the staff which so willingly stayed late to assist the society in its work.

Forthcoming Meetings

A summary of forthcoming meetings in London and other cities will be published prior to the opening of the next session.

In the meantime, the attention of members may be drawn to the following provisional arrangements.

In London the opening meeting on October 8 will be devoted to the presidential address by Professor J. T. MacGregor-Morris on "The Arc as a Standard of Light," which will be held, by permission, in the lecture theatre of the Royal Institution. Subsequent meetings will be held at the E.L.M.A. Lighting Service Bureau on October 22, when a paper reviewing industrial lighting in relation to the black-out will be read by Mr. H. C. Weston, and on December 10, when it is hoped to arrange a series of demonstrations illustrating the importance of contrast in illuminating engineering. Other papers on the visibility of distant coloured lights, vision in very weak light, and other topics are in prospect for the remainder of the session.

The programmes of the various Local Centres are also on the way to completion. It will be recalled that, in view of the national importance of factory lighting at the present time, and the special problems arising through the black-out (which has resulted in the exclusion of natural light during the daytime in many factories), Local Centres were asked to make early provision in their programmes for meetings on this subject. The North Midland Centre is accordingly devoting a special meeting in October to the industrial lighting problems. Similar meetings are being arranged in Glasgow (October 16), Manchester (October 17), Birmingham (October 11), and Nottingham (January 31, 1941). The addresses in the last three cases are to be delivered by Mr. R. Maxted.

It is also reported that several meetings in the month of September have been arranged. Thus, in Birmingham and Nottingham, addresses by the new chairmen, Dr. W. M. Hampton and Professor H. Cotton, have been arranged for September 13 and September 27 respectively.

A meeting is also in prospect on September 9 in Coventry, where efforts to establish the nucleus of another Local Sub-Centre are now being made.

The Illuminating Engineering Society is not, as a body, responsible for the opinions expressed by individual authors or speakers.

With a view to avoiding possible confusion with other publications, reference to these Transactions should be in the form:—"Trans. Illum. Eng. Soc. (London)."

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THE RELATIVE LUMINOSITY CURVE FOR THE HUMAN EYE AND THE STANDARD PHOTOMETRIC OBSERVER

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(Paper received August, 1940)

SUMMARY.

This paper first outlines the problems encountered in the photometry of coloured light sources, in particular as they are associated with the colour-characteristics of the eye. The optimum conditions for such work are shortly discussed. In the light of these findings the various experimental determinations of the mean relative luminosity function are examined seriatim under two headings—first, the investigations forming the basis of the agreed Standard Curve, and, second, more recent measurements differing somewhat from the older ones. Possible reasons or the observed differences are enumerated and examined.

The author concludes that there are at present no certain grounds for disputing the acceptability of the Standard Curve, and supports this conclusion with evidence derived from general photometric experience. A final section of the paper deals with the peculiar difficulties encountered in heterochromatic photometry at low brightness-levels, where the colour sensitivity of the eye varies greatly with the level used.

1. Introduction.

Common agreement upon a standard relative luminosity curve is necessary in order to provide a uniform basis for the expression of the results of heterochromatic photometry and of colorimetry. The standard need not necessarily be the real average characteristic for a large number of human eyes, but in order to be acceptable it must not lead to appreciable differences between results based on direct observation and those based on spectrophotometric measurement. The criterion of acceptability is clearly more stringent the greater the difference in relative energy distributions encountered in the particular operation in question.

In 1924 the Commission Internationale de l'Eclairage adopted a table of values of relative luminosity factor as standard(1).

This was in fact based on measured values for a large number of observers(2). At that time most photometric operations were concerned with simple temperature radiators, and the active factor in determining the departure of any one observer's results from the mean, in presence of a colour difference, was the *general position* of his relative luminosity curve in the spectrum. *Shape* of the curve mattered little, within colour normal limits. Thus the simple Y/B ratio test (3, 4, 5) served to characterise the individual observer quite well. In brief, the position did not demand that the standard luminosity curve, in order to be acceptable, should necessarily be a very close approximation to the real average curve. Present conditions, however, involving comparisons in which much greater differences in energy distribution occur, even when colour-match filters are used, impose stricter limits to the allowable departure of the standard curve from the true mean curve if directly observed results (as by the flicker method) are not to differ appreciably from results based on spectrophotometry and calculation. The scatter of individual results may in such cases be relatively large and bear little, if any, useful correlation with Y/B ratios(6). It will, in fact, be influenced largely by the *shapes* as well as the *general dispositions* of individual luminosity curves, and a relatively large number of observers may be necessary to obtain a fair mean result. The data adopted as standard cannot, then, differ greatly from the real mean visual characteristic without introducing inconsistency between the results obtained by various methods of measurement.

It is mainly in this sense of a more stringent criterion of acceptability that recent luminosity measurements, giving curves differing from the 1924 C.I.E. standard, have challenged the 1924 curve as representing the "standard observer." Recent determinations differ on the whole systematically from the C.I.E. curve in giving greater weight to the luminosity values at the longer wavelengths. Possible reasons for the difference must be examined, first, in case the photometric conditions are not sufficiently alike in all cases. Second, the possibility of changes, for whatever reason, in individual or mean curves, must not be dismissed.

II. Conditions of Measurement.

With certain recent exceptions, the accumulated experience of workers who have studied the conditions likely to lead to the highest degree of reproduci-

bility in the results of heterochromatic comparisons confirms the findings of Ives(7).

He gave, as the optimum conditions:—

Field size 2° diameter.

Field brightness 2.5—3.5 mL*.

Field surround of 25° diameter, slightly less bright than the 2° field.

Certain matters require particular notice here, however, since they must be kept in mind in reviewing work on the luminosity function. Some concern important details which have apparently been overlooked by certain workers; others concern the results of recent research having some bearing upon the Ives standard conditions.

In determinations of the relative luminosity function, selectivity in the photometer test surface or optical system (if any) may play a part. Some workers omit reference to any allowance for such selectivity. Others assume that magnesium oxide as a test surface is non-selective. The selectivity concerned, however, in this case is not that for integral light, but for the particular angles of incidence and reflection used. In this sense the 100 per cent. integral reflectivity of magnesium oxide is not conclusive evidence of non-selectivity, and there seems to be no published information on this question. Further, it is preferable to use only a simple optical system, or none at all, when an ordinary test surface is employed.

The main effect of an artificial exit pupil in the photometer is to reduce the effective brightness by reducing the retinal illumination. In certain cases of both older and more recent investigations, corrections on this account have to be made to the brightness figures as stated by the authors. There is, however, in addition, the Stiles-Crawford effect (8, 9), due to which the visual sensation of brightness produced by a small pencil of light entering the pupil of the eye varies with the point of entry. The variation is not the same for light of different wavelengths. This is an effect frequently overlooked. Vision by the full natural eye pupil is therefore definitely to be preferred to the use of an artificial pupil.

Several recent workers have questioned whether a field diameter of 2° is suitable, on the ground that for rod-free vision and avoidance of field-size effect smaller fields may be necessary. Fedorov (10) finds a marked field-size effect as between 1.5° and 2°, though adducing other possible causes. Jaggi (11) finds a definite effect down to 1.2°. Dresler (12) uses a field of 1° 10′ for the same reason. Jainski (13) gives relative luminosity curves for three observers for field sizes of 1.2°, 2°, and 6°. These show successive extension towards the shorter wavelengths in that order, thus showing a field-size effect down to 1.2° and also controverting the conclusions of Ives (14) regarding the existence of a *reversed* field-size effect for the flicker photometer. Preston (15), on the other hand, finds no important effect as between 1° and 2° fields.

It is interesting to note that groups of experimental relative luminosity curves showing the field-size effect, and plotted in the usual way with equal maxima, often run together at the red end of the spectrum beyond about 0.64 μ, which, according to Bender (16) and Kohlrausch (17), is near the long-wave limit of rod vision. Beyond this limit cone vision *alone* probably occurs.

This lends support to the view that the luminosity function might prove independent of field size for field sizes small enough to ensure rod-free vision, and that therefore the standard field size should be not greater than the upper limit of this range (which is no doubt less than 2° diameter for most eyes). In theory, there is nothing to dispute this view. In practice, however, fields of diameter less than 2° are fatiguing. Moreover, the large majority of workers agree that the influence of field size, if not entirely absent, is small at and below 2°.

The Purkinje effect also diminishes in magnitude with reduction in field size—or rather the value of brightness below which it becomes appreciable diminishes. Rosenberg (18) found such a diminution down to a field size of 1.4°. Jaggi (11), Dresler (19), and other recent workers find the *inverse* Purkinje effect to be appreciable over brightness ranges between 0.1 and 600 mL for a field size as low as 1.2°, though there appears to be a brightness region near 1.0 mL where the effect is minimum. It is generally held that the Purkinje effect is absent under steady illumination for true foveal or rod-free vision in the majority of observers. The argument, on these grounds, in support of a standard field of less than 2° diameter is again theoretical rather than practical. That a standard field diameter of 2° is likely to lead to the most consistent results *in practice* is therefore not seriously disputed by the recent work on the field size and Purkinje effects.

A breakdown in the additivity law, in presence of a colour difference, such as is envisaged by Dresler (20), might clearly vitiate certain of the determinations of relative luminosity curves. Its effect would

*mL = millilambert.

not be eliminated in the cascade method, where large colour differences are avoided by comparing luminosities of adjacent spectral regions step by step through the spectrum, since it would be additive over the steps and depend only on the total spectral range covered. Further, if it existed for the equality of brightness method and not for the flicker method, the two methods would give discordant results. This is by no means proven—rather the reverse is true.

The effect, if and where it is found, however, may probably be accounted for by a failure on the part of the observer to dissociate a psychological quality of colour from the pure brightness sensation. If so, it may well result from a lack of observational experience and an uncertainty in the criterion employed.

To summarise, it may be said that there is considerable evidence that the equality of brightness and flicker methods give the same results, within the limits of experimental error ([6], [21]), when used under the standard conditions given above, and, together with the C.I.E. luminosity curve, provide a consistent photometric scale when used by observers having sufficient experience. It is therefore important to note to what degree each investigator has adhered to these standard conditions in making measurements of the relative luminosity function.

III. The Experimental Basis of the C.I.E. Standard Observer.

In the main, the investigations taken as a basis for the 1924 C.I.E. curve conformed fairly closely to the desirable conditions, though the importance of the photometric conditions was appreciated less then than it is now.

1. *Ives*([14]), in 1912, studied the effect of photometric conditions and determined the curves for eighteen observers by the flicker method([7]). He used a 2° field, 25° surround, effective field brightness 2.5 mL, and exit slit 2 mm. × 0.5 mm. The measurements covered the range 0.481μ to 0.655μ, the results being extrapolated to 0.44μ and 0.68μ. The maximum ordinate of the mean curve was at 0.550μ.

2. *Nutting*([22]), under almost identical conditions, used twenty-one observers and obtained a maximum ordinate at 0.556μ.

3. *Coblentz and Emerson*([23]) used 125 observers, flicker method, and 2° field. The field appears to have been set at an actual brightness of 5.0 mL, and viewed through a slit 2.63 mm. × 0.52 mm. The effective brightness was therefore about 0.7 mL ([24]). The spectral range covered was 0.49 — 0.69μ, with extension to 0.435μ and 0.75μ at a lower brightness for some observers. The maximum ordinate was found to be at 0.558 μ.

4. *Hyde, Forsythe, and Cady*([25]) employed the equality of brightness cascade method. The field size was 7°. An artificial exit pupil of area 0.6 sq. mm. was used, and the effective field brightness varied between about 0.2 and 1.0 mL. The resultant mean curve was displaced on the whole somewhat toward the shorter wavelengths as compared with other determinations. The authors considered that this was due to the use of the equality of brightness method, but it seems more possibly to have resulted from the large field and lower brightness used. The maximum ordinate was at 0.556μ however.

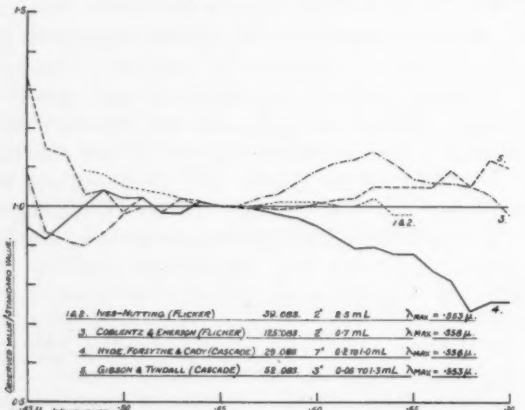
5. *Gibson and Tyndall*([26]) used the cascade method to augment available data by this method and settle if possible the question of agreement or otherwise with the flicker method. Some fifty-two observers took part in the range of 0.49-0.68μ and thirty-eight of these continued their readings to 0.43μ and 0.74μ. The photometer field was a 3° divided circle, and effective field brightness ranged approximately between 1.3 and 0.05 mL. An artificial exit pupil ranging between 0.25 sq. mm. and 0.75 sq. mm. in area was used. The maximum ordinate of the mean curve was at 0.553μ.

For a detailed comparison between the results of these determinations reference should be made to Gibson and Tyndall's paper. The authors conclude in particular that there is no certain difference between results for the cascade equality of brightness and the flicker methods when both are used under the conditions laid down by Ives([7]). In all these determinations except those of Ives and Nutting the effective field brightness was distinctly lower than 2.5 mL, and the other conditions varied to a certain extent. Nevertheless, the degree of agreement realised was satisfactory and the results were used as the basis of the 1924 C.I.E. standard curve([2]). The deviations of the different mean curves from the standard are shown in Fig. 1.

IV. Recent Investigations.

A revival of interest in the luminosity function has followed the advent of the discharge lamp. That the stated intensity of any such lamp

will depend to a considerable extent on the particular luminosity curve assumed in the measurement is, in fact, a sound reason for using a standard curve not too widely different from the real mean


1.5
1.0
0.5
1&2.
3.
4.
5.
1&2. Ives-Nutting (Flicker) 30 cds. 2° 2.5 mL λmax = 552 μ.
3. Coblentz & Emerson (Flicker) 125 cds 2° 0.7 mL λmax = 558 μ.
4. Hyde, Forsythe & Cady (Cascade) 29 cds 7° 0.2 to 1.0 mL λmax = 556 μ.
5. Gibson & Tyndall (Cascade) 52 cds 3° 0.05 to 1.3 mL λmax = 553 μ.
Observed value/Standard value.
·43 μ Wavelength
·50
·55
·60
·65
·70
FIG. 1. Showing departures of results of determinations 1-5 of luminosity factor from the standard values. The latter are taken as unity throughout.

curve, if only in order to ensure that the flicker and the colour-match equality of brightness methods will not give conflicting results.

Recent investigations are notable for two new lines of attack. In the first, monochromatic light is obtained directly from a discharge lamp with an isolating filter. Measurements are here confined to spectrum lines obtainable in practice with sufficient intensity and purity. In the second, direct measurements of total transmission are made on series of selective filters operative on different regions throughout the visible spectrum. From these the form of luminosity curve most consistent with them is calculated. Neither approach lends itself to the equality of brightness method, since full colour differences are encountered.

A new technical detail in several researches is the use of a calibrated photocell for the energy measurements required by the first of the two procedures just mentioned.

6.* *Arndt*(27), using a mercury vapour lamp, measured $K\dagger_{578}/K_{546}$ for forty-seven colour-normal observers, using a Bechstein photometer, 1.5° field and 30° surround. No mention is made of the material of the test surface or its selectivity. The stated field brightness of 3.0 mL applies to this surface, no indication of pupil size being given. It is likely that an artificial pupil was used, and that the effective brightness was considerably less. Arndt states, however, that raising the brightness to 10.0 mL did not influence the mean result, which was $K_{578}/K_{546} = 1.035$ (Standard C.I.E. value = 0.89). Arndt suggests that this result points to a curve with maximum ordinate at 0.565 μ.

Energy measurements were made with a calibrated selenium rectifier photocell, on light incident on the photometer.

7. *Rieck*(28) by a similar method obtained $K_{578}/K_{546} = 1.04$ for four observers only.

8. *Federov and Fedorova*(10) determined their own curves by the cascade method, first, with 1.5° field with daylight illumination in the laboratory, second, with field size 2° and darkened laboratory. The second result shows a relative displacement of the curves toward the blue, except in the red beyond 0.64 μ. The authors consider this to be due to partial dark adaptation produced by the dark-room, and to the 2° field not entirely eliminating rod vision(29).

9. *Dresler*(12) extended Arndt's work by inclusion of the sodium doublet at 0.589 μ. He used a similar method and photocell but without a surround field, and in an illuminated room. The stated field brightness of 1.0 mL is subject to the same remark as in 6 above. The mean results for thirty-four observers were $K_{589}/K_{546}=0.94$ for a 1° 10′ field and 0.99 for a 7° field (Standard C.I.E. value =0.77). To obtain his complete luminosity curve Dresler employed seventeen observers representative of the larger group to measure the total transmission of four colour filters, and then calculated the relative luminosity curve most consistent with these and with the luminosity ratios determined by Arndt and himself. This calculated curve was displaced toward the red, as compared with the C.I.E. standard, except (again) on the long wave side of 0.64 μ approximately. The maximum was at 0.56 μ. Dresler lays stress on the necessity of using a small field of about 1° diameter to obtain true cone vision.

10. *Preston*(15) in 1937 measured K_{578}/K_{546} for sixteen observers with a Guild photometer, 2° field and bright surround. The field illumination was 25—30 metre candles on magnesium oxide viewed directly with full pupil (i.e., effective brightness 2.5—3.0 mL). The mean result was $K_{578}/K_{546}=0.90$, in good agreement with the C.I.E. standard. Energy measurements were made with an Elster-Geitel type vacuum photocell with K—AgO—Ag molecular film cathode, fitted with a diffusing disc, this assembly being calibrated in turn against a thermopile. Appropriate tests for linearity of cell and thermopile characteristics were made.

11. *Jainski*(13) in 1938 determined complete

* Numbering continued from Section III.
† K = luminosity function, subscript = wavelength in mμ.

curves for sixty observers using a step-by-step method with the flicker photometer, and field size 1.2°. Limits of field brightness are stated as 20.0—80.0 mL, values which appear to apply before reduction by an ocular system and artificial pupil. (See recent comments by Dresler(32)). Energy measurements were made directly with a thermopile. The mean result was a curve similar to Dresler's, but relatively higher in the red and having a maximum at 0.565 μ: Jainski also found the displacement with field size mentioned above (II.) and concluded that use of a field size of 6° would lead to a curve in agreement with the C.I.E. curve.

12. *Jaggi*(11) determined a curve under very high brightness, which agreed in position with the C.I.E. curve, but was narrower in shape. He also used the "filter series" method for fourteen observers, with Bechstein photometer and usual test surface, field size 1.2°, surround field, and field brightness 5.0 mL without allowance (apparently) for optical system and exit pupil. The result was a curve intermediate in shape between Dresler's and the C.I.E. standard, with maximum at 0.550 μ.

13. *Preston*(30) in 1939 extended his previous investigation, under identical conditions, to a group of twenty observers, and the additional wave-lengths 0.5086 μ (Cd), 0.5893 μ (Na), and 0.6439 μ (Cd).

The results were:—

K_{5086}/K_{5461} = 0.462 (C.I.E. data give 0.475)
K_{5780}/K_{5461} = 0.927 (C.I.E. data give 0.889)
K_{5893}/K_{5461} = 0.835 (C.I.E. data give 0.765)
K_{6439}/K_{5461} = 0.143 (C.I.E. data give 0.146)

These values indicate a curve agreeing with the C.I.E. curve except in the region 0.56 μ — 0.63 μ, where it is higher by an amount up to 11 per cent., part of this difference being accounted for on statistical grounds based on the number of observers taking part, and the spread of their results.

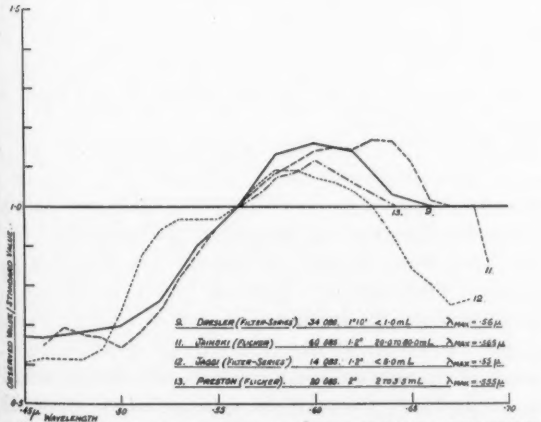


Fig. 2. Showing departures of results of determinations 9, 11, 12 and 13 of luminosity factor from the standard values. The latter are taken as unity throughout.

14. *Forsythe, Barnes, and Shrider*(21) give evidence that the mean measured total transmission factors of certain colour filters by a group of observers were quite in accord with calculated values based on spectrophotometry and the C.I.E. luminosity data. They also measured K_{578}/K_{546} for eighteen observers, using an Ives-Brady flicker photometer with 2° field, and obtained a value only 2 per cent. different from the C.I.E. figure.

Figure 2 shows the departure of some recent curves from the C.I.E. standard.

V. Evidence from Photometry, Colorimetry, and the Y/B Ratio Test.

A very large amount of evidence concerning the suitability of the C.I.E. standard eye has accumulated in the fields of photometry and colorimetry. While of an indirect nature, and not affording precise information as to the closeness of the C.I.E. curve to the real average curve, it involves enormous numbers of observations confirming the belief that the C.I.E. data is not seriously unrepresentative of ordinary vision, and is satisfactory as a standard. On the photometric side there is the general agreement between direct (e.g., flicker) methods and methods involving the use of colour filters whose transmissions are calculated by the use of the C.I.E. data. On the colorimetric side, the standard luminosity data are incorporated in the spectral mixture curves of the C.I.E. standard observer. If the data were seriously in error the discrepancies between colours as measured by ordinary observers, and as calculated from spectrophotometric data would be much greater than is found to be the case in fact.

Again, the consistency of early measurements on many observers in giving a mean Y/B ratio near to unity is well known. This in itself was evidence of the "goodness" of the C.I.E. curve as representing the real average eye, since the calculated ratio for the standard filters used, based on spectrophotometry and the C.I.E. curve, was very close to unity. Unfortunately, all too many workers have overlooked this simple qualitative test which might be applied to their observers. Forsythe, Barnes, and Shrider (IV., 14) measured the mean Y/B ratio of their observer group, with a result of 0.989. Preston (IV., 10) gives the mean ratio for his 16 observer group as 1.003 measured in 1935. Re-measurement of the same

group in 1939 gave a ratio of 1.011, while the whole 20 observer group then taking part (IV., 13) had a mean ratio of 1.021. None of these mean values indicates any difference between the C.I.E. standard curve and the experimental mean curve, for their departures from unity are less than the calculated likely variations, on statistical grounds, due to the smallness of the observer groups.

Dresler, in a private communication to the author, gives the mean Y/B ratio of twenty-one of his observers as 1.032, while their mean ratio K_{589}/K_{546} is 0.932. These two figures are hardly consistent with one and the same mean luminosity curve, unless it be of a highly improbable shape. Moreover, Dresler's experimental luminosity curve (IV., 9) gives a calculated Y/B ratio of about 1.10. Other recent experimental curves would lead to even higher values. Had the respective experimenters determined the Y/B ratios of their observers their findings would carry much greater weight.

There are thus no available Y/B measurements inconsistent with a close agreement between the C.I.E. standard luminosity curve and the true mean curve.

Taken as a whole, therefore, the indirect evidence in support of the C.I.E. curve as a satisfactory standard is so strong as to be practically conclusive and we are led to examine the reasons for the differences between the older and more recent determinations of the luminosity curve.

VI. Discussion of the Data.

As already indicated, two distinct questions arise from consideration of the various experimental results.

A. Reasons for the Variability of Observed Curves.—In comparison with later work certain features of determinations 1-5 are to be noted. First, the limits of wavelength for the maximum ordinate are 0.550 μ (Ives) and 0.558 μ (Coblentz and Emerson). This range is smaller than, and systematically different from that for the later work. Second, systematic differences between the results of the major determinations 3 and 5 occur mainly in the range 0.55 μ to 0.64 μ, the flicker determination giving the higher values. The flicker determination of Preston gives similarly higher values in just the same region. In both these latter cases energy values were derived more or less directly from thermopile readings, whereas in most of the earlier work energy values were in general obtained by calculation from the known characteristic of the light source and the measured transmission of the optical system. The latter measurement has uncertainties, more especially when polarising systems are used to control the light input. Coblentz and Emerson, however, used an acetylene flame as light source and made direct energy measurements at the exit slit.

Thus, in cases where energy values are used, but not measured directly, one not unimportant source of error may be in the transmission measurements on the optical system employed.

Referring now to the recent work as a whole we find that it is again principally in the spectral region of 0.55 μ to 0.64 μ that these determinations differ most markedly from the standard and from each other.

With the exception of work by Forsythe, Barnes, and Shrider, and that by Preston, recent results support curves lying distinctly toward the red end of the spectrum (except perhaps beyond 0.64 μ), as compared with the older findings (1-5). The displacement of the maximum is of the order of 100-150 Å. This is so for work which conforms apparently (not always certainly) to the appropriate conditions, and even in such work the variability of the results is often unexpectedly large if it is due solely to experimental error.

Emphasis must, of course, be laid upon the very real difficulties, frequently only very inadequately realised, in obtaining accurate energy values from which to calculate the results—even when these are determined directly by a measurement in situ with a thermoelement. These difficulties are not necessarily increased by the use of a calibrated photocell as intermediary, provided a suitable cell is chosen, and is used to bridge the gap between inconveniently low energy values encountered in the actual measurements and the more adequate levels which may be used for the calibration of the cell; but for accurate work the vacuum emission photocell is greatly superior to the rectifier type of cell used by several investigators.

However, it cannot be assumed that errors in energy measurements would account for a generally systematic departure from the C.I.E. curve shown by results obtained in England, Switzerland, Germany, and the U.S.S.R. Moreover, results obtained by the "filter-series" method, such as those of Dresler and Jaggi, are independent of energy values beyond the assumed spectral energy distribution of a lamp of known colour temperature. While admitting, therefore, the difficulty associated with the energy basis of many determinations of the

luminosity function, other influential factors are not to be discounted.

It is regrettable that workers who emphasise the importance of strict cone vision, and claim an appreciable field size effect inside the 2° or 3° region, have not themselves at one and the same time endeavoured to compare results for different field sizes of less than 3°. Most comparisons have been between sizes such as 1° and 7° (see IV., 9). The factor of field brightness is in dispute only in those cases where sufficient data for calculating the *effective* field brightness are not given. These are not few, relatively speaking. Again, the influence of any general displacement of the adaptation level during measurements, due to darkness or otherwise of the photometer room, is unlikely to be appreciable with proper photometer field conditions. Such a possible effect is least aptly examined by using the room itself as the adapting field. There remain some possible technical sources of error, such as selectivity of photometer test surfaces or optical trains, often not taken into consideration.

With regard to the possibility of real changes or differences in individual or mean luminosity curves, racial differentiation is not to be overlooked, although if it exists it is curious that it has not been detected earlier. The idea of dietetic influence put forward by the present author([30]) is attractive, perhaps because mainly hypothetical at present. However, deficiency in vitamin A, and the associated carotenoids from which the body manufactures vitamin A, is well known to have strikingly large effects in raising the absolute threshold([31]). It is unlikely that such effects are not associated with changes in colour sensitivity also. These carotenoids are closely related chemically with visual purple and other important substances present in the retina. Complete starvation of them for a sufficient period produces a serious form of blindness. Dresler has recently recorded([32]) a seasonal change in the luminosity curves for two observers, possibly connected with such effects.

It is thus difficult, at present at least, to assign any real cause, or degree of importance in the photometric sense, to the divergences of recent experiments, though the results certainly indicate many fields for research of a more exact nature, under more standardised conditions.

B. Acceptability of the C.I.E. Standard Curve.—In view of these remarks and the relative degree of consistency of the earlier determinations, there is no certain ground for maintaining that the standard curve is not a good representation of the true mean curve under the " Ives " recommended conditions. In fact the only valid reason for making a change in the present standard would be the establishment of an unimpeachable new experimental curve so markedly different from the standard as to show that the use of the latter led to a photometric scale only poorly representative of what the eye really sees, or to marked inconsistencies between different photometric methods. This reason does not at present exist, and international agreement to maintain in force the 1924 curve was recorded at the 1939 Plenary Session of the Commission Internationale de l'Eclairage in the form of an official resolution, which states that " There is no case for changing the factors of luminosity at present in force."

As an illustration of what the position might be if the standard curve were a very bad representation of the facts, we may fittingly conclude with a note on the use of the eye for measurements in the region of low brightness, where the colour characteristics of the eye are very different from the normal.

VII. Visual Photometry at Low Brightnesses.

When the eye is fully dark adapted it becomes comparatively much more blue sensitive (Purkinje effect), the maximum of the luminosity curve (scotopic) being situated at about 0.502 μ. Between the scotopic and photopic levels the eye behaves as a receptor of varying colour sensitivity. Thus, if two phosphorescent substances of different colours, but having similar decay curves in the physical sense, commence their decay period with apparently equal brightnesses, they will appear anything but equally bright after the lapse of an hour or two, although each will be radiating energy at the same percentage of its initial rate.

Or we may measure the brightness of a dimly luminous material of a certain colour by comparison with a white light source and colour match filter. We may use the standard photopic luminosity curve in calculating the filter transmission, and so express the brightness of the material in terms of the usual units, obtaining a properly reproducible result. The trouble arises when we discover that we can measure in this way the brightness of another phosphorescent material of different colour from the first, obtain the same result on paper, and yet find that the two materials

obviously do not appear equally bright. The reason lies in the method of measurement, for the standard luminosity curve is not applicable at the low level of brightness used, and so the calculated transmissions of the colour match filters are wrong. If we used the luminosity data proper to the brightness level used, we should obtain proper agreement between what is measured and what is seen. Unfortunately, there is a different luminosity curve appropriate to every different brightness level in this region, and the colour match filter method is therefore of no practical use.

Instead, a proposal has been made to compare the brightness of a coloured luminescent material with that of a white surface of specified colour temperature, and reduce the brightness of the white surface to apparent equality. The brightness of the luminescent material is then expressed as equal to the value for the white surface. This in its turn is derived from the brightness unit under photopic conditions subject to reduction by strictly "neutral" methods such as the sector disc, or use of the inverse square law. This procedure clearly ensures that materials appearing equally bright will be assigned the same brightness figure, since they will all be equated to the same white brightness. This actual figure will of course depend on the character of the white light, since the amount of *apparent* reduction in the white caused by, say, a 1/100 sector disc, will depend on its colour temperature or spectral quality.

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The Physical Society Colour Group

At a meeting held in May last under the authority of the Council of the Physical Society it was unanimously decided to form "The Physical Society Colour Group," with the following objects:—

(i) To provide an opportunity for the various groups of people concerned with colour—physicists, chemists, industrialists, etc.—to meet and become familiar with each other's problems.

(ii) To enable a representative opinion to be formed on various questions of standardisation, specification, nomenclature, etc.

(iii) Generally to encourage colorimetric investigations and to ensure that this country shall keep abreast of developments abroad.

At the meeting referred to above the following officers of the Group were elected:—

Chairman.....Dr. W. D. Wright.
Hon. Secretary.....Mr. H. D. Murray.
Committee.....Mr. H. W. Ellis, Mr. J. Guild, and Mr. J. G. Holmes.

A number of societies have been invited to become Founder Societies of the Group and to be co-operated in its activities.

It is hoped that the first General Meeting of the Group, to be followed by the first Scientific Meeting, will be held in the middle of October next, when "Colour Tolerance" will be discussed.

In the meantime, members of the Illuminating Engineering Society interested in the objects of the Group are invited to communicate with its honorary secretary, Mr. H. D. Murray, 1, Lowther-gardens, Exhibition-road, London, S.W.7.

THE EFFECT OF FLASH FREQUENCY ON THE APPARENT INTENSITY OF FLASHING LIGHTS HAVING CONSTANT FLASH DURATION*

By A. E. SCHUIL, B.Sc. *(Member)*

(Communication from the Staff of the Research Laboratories of The General Electric Co. Ltd., Wembley, England.)

SUMMARY.

Observations were made in the laboratory, on the effect of varying the flash frequency on the apparent intensity of flashing lights having durations of 1/40th second and 1/10th second. The majority of the readings were taken at an illumination level of 0.5 mile-candle on the eye. This is the desirable lower limit of illumination on the eye for adequate conspicuity of marine and aviation lights. Observations had been reported indicating that when distant lights were flashed at frequencies above that at which the flashes were distinct, the intensity appeared greater than Talbot's Law would suggest. It is shown that these observations, which were not made under controlled conditions, were evidently in error. Up to frequencies of about 5 flashes per second the light appears as flashing and its apparent intensity can be obtained from the fixed light intensity by the application of the Blondel-Rey correction. At higher frequencies than about 13 flashes per second (with the shorter flashes) the light appears continuous and the Blondel-Rey correction is no longer applicable; instead Talbot's Law applies. Between about 5 and 13 flashes per second the light appears to flicker and the apparent intensity is greater than either Talbot's Law or the Blondel-Rey correction would indicate. This flickering light is not thought to be of any practical value as its apparent intensity is less than a flashing light consuming the same amount of energy but giving a readable flashing indication.

Introduction.

A knowledge of the apparent intensity of flashing lights is of importance in sea and air navigation. It is already well known that the effect of flashing a light is to reduce its apparent intensity, and the influence of varying the duration of the flash has been investigated by Blondel and Rey(1), Toulmin Smith and Green(2), and by Hampton(3). The basic Blondel-Rey formula is $\frac{I_L}{I} = \frac{t}{a+t}$, where I_L is the apparent intensity of the flashing light, I its intensity when not flashed, t the duration of the flash in seconds, and a, a constant. The constant a has been found to vary with the illumination level at the observer's eye, and Hampton(3) has proposed that the value be expressed in the form, $a = \left(\frac{0.0255}{E}\right)^{0.81}$ where E is the illumination on the observer's eye in mile-candles*.

These formulae are derived from the results of investigations in which the eclipse period between the flashes was of the order of one second, or longer, and the flashes were therefore quite distinct. They show that, although the apparent intensity of a flashing light is lower than its actual intensity during the flash, it is considerably higher than it would be if the same light energy were emitted by a steady light.

There had been reports that if a distant source were flashed above the frequency at which the flashes were distinct, the source would still appear to have a higher intensity than a continuous light of the same light energy output, i.e., it would be brighter than Talbot's Law† would suggest. Hyde(4) in an investigation on rotating sectors as used in photometry, found that at normal photometric illumination levels, Talbot's Law was obeyed for all frequencies down to that at which flicker was present. Results do not appear to have been given before for distant point sources, and the present investigation was undertaken to determine the effect on the intensity of a flashing light of constant flash duration, of varying the frequency from values at which the flashes are separated by a long interval (and the Blondel-Rey Law applies) to those at which no flicker was present (and Talbot's Law is presumed to apply).

Experimental Work.

In making visual tests on flashing lights under actual field conditions, there are so many variables beyond the experimenter's control that it is difficult

*1 mile-candle (the illumination produced on a surface 1 mile from a source of intensity 1 candle and normal to the incident light) $= 3.6 \times 10^{-8}$ ft.c.

† Talbot's Law states that, if the eye is subjected alternately to a field of a given brightness, and to darkness, at a frequency above the critical frequency, the sensation produced is the same as that produced by a field of steady brightness reduced in the proportion of the period of brightness to the period of the cycle.

★Communicated. Work conducted at the suggestion of the British Standards Institution's Technical Committee ELG/16 on Lighthouse Intensities.

to make such tests sufficiently accurate to serve as more than a check on laboratory experiments.

The tests in this instance were therefore carried out in the laboratory, the distant lights being simulated by pinholes placed in front of opal screens of known brightness. One of the point sources was of fixed intensity and was used as the comparison source, whilst the other was given a flashing character by placing in front of it a revolving sector whose aperture and speed of rotation could be varied. The actual intensity of the flashing light was controlled by varying the brightness of the opal screen by means of which it was produced. The opal screen in this instance was illuminated by light from a large condenser lens which was placed in front of a filament lamp. The aperture of the lens, and hence the brightness of the opal, could be varied by means of an iris diaphragm. Readings of the brightness of the opal for various settings of the iris-operating lever were taken with a visual photometer, and from these the actual intensity of the pinhole for any setting of the lever could be calculated. The pinholes used for the two sources were of identical size and shape, the diameter being chosen to make the lights effectively point sources([5]). In order to avoid any error due to difference of colour, the two opal panels were matched by suitable choice of lamp voltages.

The sources were viewed by the observer through a plane mirror about 15 ft. away from the apparatus so that the effective distance of view was about 30 ft. Other observations were made at a distance of 90 ft., with the source size and brightness suitably adjusted, and the two sets of observations agreed closely.

The fixed light was adjusted to give an illumination on the eye of 0.5 mile-candle (making allowance for the reflection factor of the mirror). This value corresponds to 0.67 sea-mile-candle, which is the accepted lowest limit for adequate conspicuity of a light, and the choice of such a figure brings the work into line with the earlier work of Toulmin Smith and Green([2]). Observations were also made at an illumination level on the eye of 2 mile-candles.

The observer was asked to adjust the intensity of the flashing light until it appeared to him to be the same as that of the fixed comparison light. This he did by adjusting the control lever of the iris diaphragm already described. Several readings were taken by each observer at each setting of the flash frequency, and the positions of the iris lever were noted by a second observer, so that the person making the settings could not be influenced sub-consciously by his previous readings. The spread of readings by a given observer was, in general, not as great as the difference between individuals.

The sources were arranged so that the space between them subtended an angle of about 2 deg. at the eye of the observer, since it was felt desirable to make it impossible to fixate both sources simultaneously. When the separation of such sources is less than one degree, the eye attempts to image both sources on the fovea, and the result is that neither is correctly fixated, and the images fall on that part of the retina where the sensitivity gradient is very steep([6]). Placing the sources at a greater angle apart enables the observer to look deliberately at one or the other source. Some observers preferred to use a device which enabled them to look at each source alone, so that they could fixate it definitely and then change rapidly over to the other source for comparison. Their results did not differ materially from the others.

Results.

Fig. 1 shows the relation between apparent intensity and total flash period (i.e., $\frac{1}{\text{frequency}}$) for a constant flash duration of 1/40th second, and the points plotted give an indication of the spread between the results of different observers. This spread appears large, but is to be expected in view of the nature of the observation which is more difficult than that experienced with a normal photometric balance. The curve is drawn through the calculated mean values. Fig. 2 shows the same relation for a constant flash duration of 1/10th second. In each curve the apparent intensity is plotted as ordinate as a percentage of the fixed light intensity, and the length in seconds of the total period (flash + eclipse) is plotted as abscissa. Thus the "character" of the light varies continuously along the curve.

For flash frequencies of the order of one flash per second the apparent intensity for a constant flash duration is independent of frequency. The values of the apparent intensity for such frequencies (approximately 20 per cent. of the fixed light intensity for flashes of 1/40th second duration, and approximately 50 per cent. for flashes of 1/10th second duration) are in close agreement with the values of 22 per cent. and 53 per cent. obtained by Toulmin Smith and Green([2]) for flashes of these durations, at an illumination level of 0.5 mile-candle.

Referring now to Fig. 1 it will be seen that as the frequency of flashing is increased, i.e., the total period is reduced, with the flash kept constant at

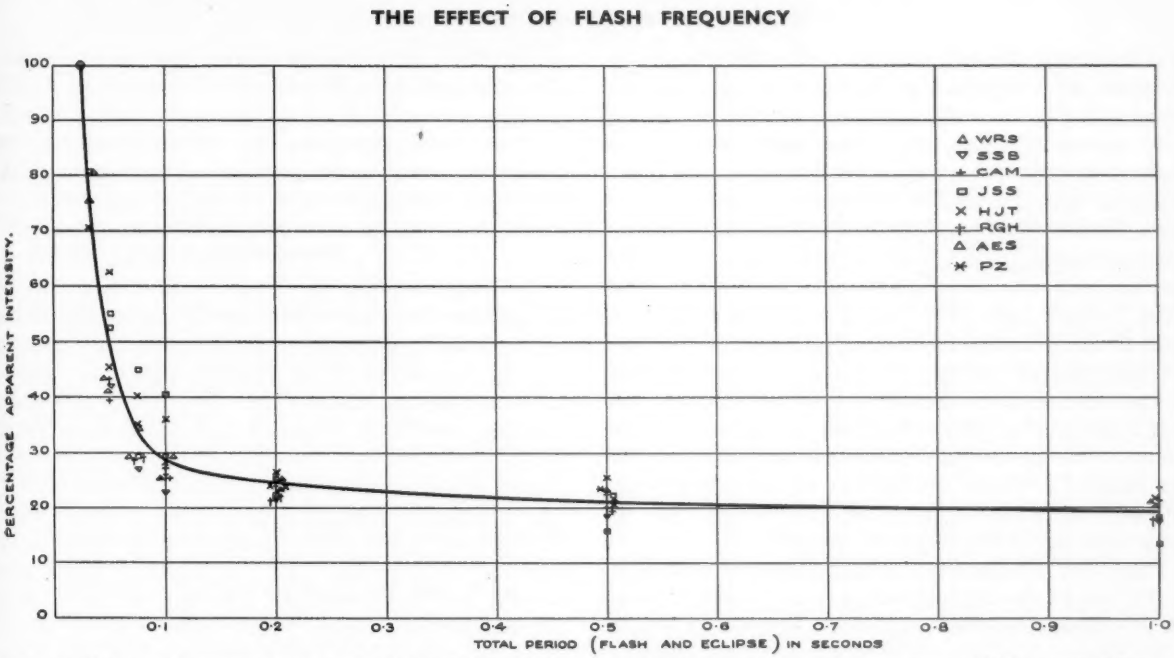

Fig. 1. Variation of apparent intensity of a flashing light with frequency of flash duration remaining constant at 1/40th second. Mean readings of various observers, with calculated mean curve.

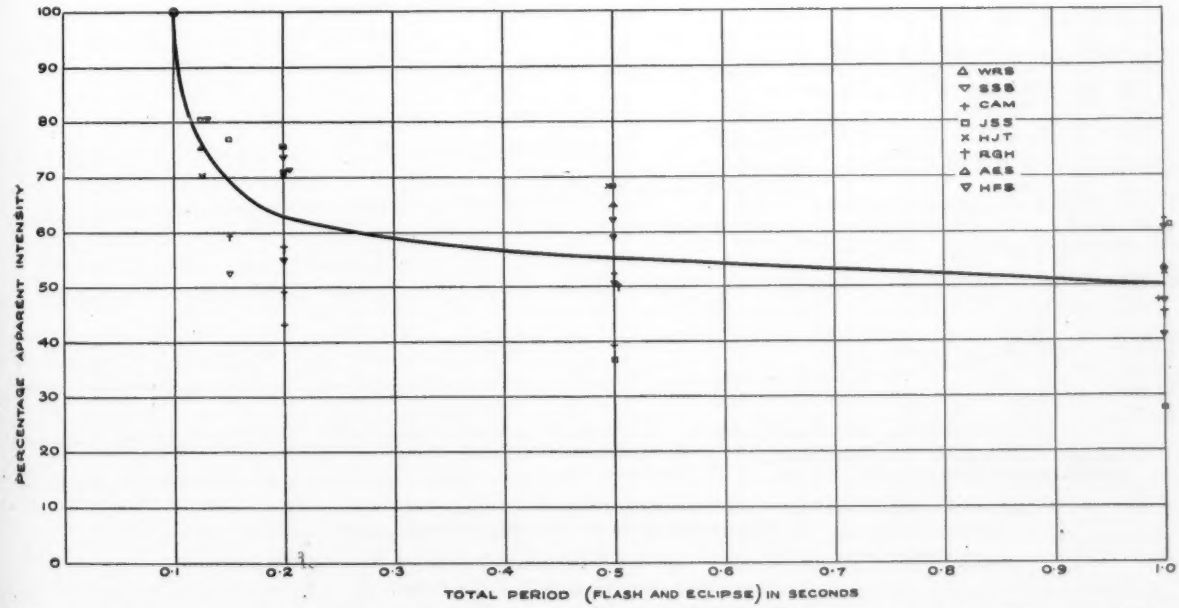

Fig. 2. Variation of apparent intensity of a flashing light with frequency of flash, the flash duration remaining constant at 1/10th second. Mean readings of various observers, with calculated mean curve.

1/40th second, the apparent intensity remains fairly constant until a period of 0.2 seconds (i.e., a frequency of five flashes per second) is reached, when, most observers agree, the light loses its definite flashing appearance although a flicker is still perceptible, until a frequency of about thirteen flashes per second is reached. Above this frequency the apparent intensity rises steeply with increasing frequency, and actually follows the curve calculated from Talbot's Law (Fig. 3). This means that for a light flashing so rapidly as to appear steady the percentage apparent intensity is equal to the percentage of the time during which the light is visible. In Fig. 3 the curve calculated from the percentage of time for which the light is visible is drawn beyond the range for which the light is apparently steady, although it is known that Talbot's Law is not intended to apply beyond this range.

The curve obtained for a flash duration of 1/10th second shows the same general characteristics as that for 1/40th second flash and is also shown in Fig. 3 with the corresponding curve calculated from Talbot's Law.

The readings taken at an illumination on the eye of 2 mile-candles showed a similar connection between flash frequency and apparent intensity to those taken at 0.5 mile-candle. These tests did not show the increase in the fixed light equivalent at 2 mile-candles as compared with the value at 0.5 mile-candle, which was noted by Toulmin Smith and Green([2]), but this does not affect the conclusions drawn in this paper.

Conclusions.

The experimental results show that it would not be possible to effect an economy in navigational lights which are to appear fixed by flashing them so rapidly that flicker is no longer apparent. Under these conditions Talbot's Law is directly applicable and the fixed-light intensity is reduced by a factor equal to the ratio of the flash duration to the total period of flash and eclipse (i.e., to the "character"). The Blondel-Rey factor is found to be applicable to all flashing lights whose indication is readable as flashing, even though the "character" may vary widely, and the fixed-light intensity is reduced by the Blondel-Rey factor which is determined by the flash duration only. When there are between five and thirteen flashes per second the light appears to be neither fixed nor flashing, but flickering. The apparent intensity of such a flickering light is somewhat greater than either of the above factors would

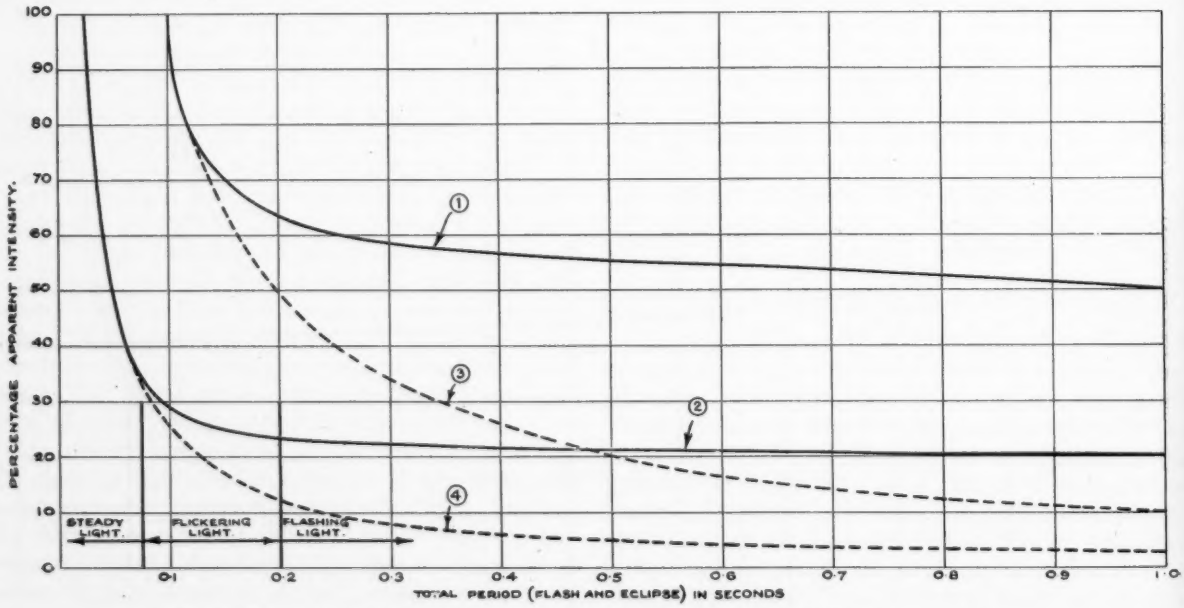

Fig. 3. Effect of varying the eclipse time of a flashing light keeping the flash duration constant.

1. Experimental curve for flash of 1/10th second.
2. Experimental curve for flash of 1/40th second.
3. Curve calculated from Talbot's Law (1/10th second flash).
4. Curve calculated from Talbot's Law (1/40th second flash).

indicate. This flickering light is not thought to be of any practical value, as its apparent intensity is always less than it would be if the same "character" were exhibited at such a frequency as to be readable, i.e., less than five flashes per second. The greatest apparent intensity for a given expenditure of energy is obtained by increasing the period of darkness between the flashes.

Application of Results to Revolving Flashing Lights.

In the experimental method used the flashes were abrupt, the light being opened and eclipsed by a rotating sector.

When the flash is produced by a revolving optical system such as that often used in a lighthouse, the time-intensity relation corresponds approximately to a sine-squared law. The effective duration of such a flash can only be calculated if the time-intensity relationship is known accurately, but this is seldom the case in practice. It has, however, been found possible to estimate the apparent intensity by the use of an appropriate modification of the Blondel-Rey formula(7):

$$I = k \frac{t}{0.2 + t} I_m$$

where t is taken as being $0.16 \frac{d}{f} T$.

- k is a constant of the optical system.
- I_m is the maximum intensity of the beam.
- d is the width of the source.
- T is the time of revolution of the optical system in seconds.
- f is the focal length of the optical system.

In this formula the value of the maximum intensity is used, but the time t is calculated in such a way as to weight it appropriately for the form of the time-intensity relationship. The experiments described in this paper have indicated that for abrupt flashes the Blondel-Rey formula will hold so long as a distinct flashing indication is given, and it seems reasonable to assume that the modified Blondel-Rey formula for revolving lights will also hold so long as the flashes are distinct.

Appendix.

Deduction from the Results on the Persistence of Ocular Sensation.

It will be seen that the actual Blondel-Rey factor (50 per cent for 1/10th second and 20 per cent. for 1/40th second) is only attained when the flashes are separated by about one second. When the interval separating the flashes is less than one second, the flash appears to have a somewhat higher intensity. This would appear to be explained if it were found that the eye continued to experience some slight sensation from a flash for as long as one second after its cessation. If such an effect exists, then when the flashes follow one another at short intervals, some residual sensation remains from each of the previous flashes which have occurred in the past second, the amount of such residual sensation decreasing with the length of time after the flash has ceased. If these residual sensations occur and are additive, the form of the curves in Figs. 1 and 2 can be explained; but more information is needed on the rate of decay of ocular sensation before such a hypothesis can be verified.

The apparent intensity of a flashing light is also affected by the fact that the sensation of vision only rises slowly after the beginning of the flash, taking some 1/20th second to reach its maximum for an abrupt flash of constant intensity(8). This is the basic explanation of the Blondel-Rey effect, and the constant "a" in the Blondel-Rey formula is an empirical figure for this "inertia" of vision. For short flashes the sensation never reaches its maximum since the flash ceases while the sensation is still rising. The rate of rise would be expected to change with varying illumination level, and this is in agreement with the fact that "a" has been shown to depend on the illumination level on the eye.

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The Illuminating Engineering Society is not, as a body, responsible for the opinions expressed by individual authors or speakers.

With a view to avoiding possible confusion with other publications, reference to these Transactions should be in the form:—"Trans. Illum. Eng. Soc. (London)."

PROVISIONAL PROGRAMME OF MEETINGS (SESSION 1940-1941)

In what follows we give a provisional list of meetings of the Society in prospect in London and elsewhere. All particulars of meetings at present available have been included, but it will be understood that in some instances arrangements for the Session have not yet been completed.

It is hoped, wherever possible, to proceed with the programme, though this naturally depends on local conditions. In the meantime, members are advised to keep this list for reference purposes. Notices of individual meetings will be issued to members resident in the areas in which they are held, and any modifications in programme will, so far as possible, be brought to their notice. For the moment the customary time has been provisionally adopted for meetings in London. In the case of some other cities (where it has hitherto been usual to hold meetings at 7 p.m. or thereabouts) no decision has yet been taken, but announcements will be made to members in due course.

GENERAL MEETINGS (LONDON).

Unless otherwise announced Meetings will be held at **6.0 p.m.** *and will be preceded by light refreshments at* **5.30 p.m.**

1940.

Tuesday, Oct. 8th. Address by the President (PROF. J. T. MACGREGOR MORRIS) on **The Arc as a Standard of Light.** *To be held at the Royal Institution, 21, Albemarle Street, London, W.1.*

Tuesday, Oct. 22nd. A Paper on **Industrial Lighting and the Black-out,** by MR. H. C. WESTON. *To be held at the E.L.M.A. Lighting Service Bureau, 2, Savoy Hill, London, W.C.2.*

Tuesday, Dec. 10th. Demonstrations illustrating **Effects of Contrast in Illuminating Engineering.** *To be held at the E.L.M.A. Lighting Service Bureau, 2, Savoy Hill, London, W.C.2.*

1941.

Tuesday, Jan. 14th. A Paper on **Fundamental Principles of Vision in Very Weak Light,** by DR. W. D. WRIGHT.

Tuesday, Feb. 11th. A Paper on **The Recognition of Coloured Light Sources,** by MR. J. G. HOLMES.

Tuesday, March 11th and **Tuesday, April 6th.** } Subjects to be announced.

Tuesday, May 13th. Annual General Meeting.

NORTH MIDLAND LOCAL CENTRE.

(*Hon. Secretary:* T. C. HOLDSWORTH, Electricity Showrooms, The Headrow, Leeds 1.)

Unless otherwise announced Meetings will be held at the Electricity Showrooms, the Headrow, Leeds, at **6.0 p.m.**

1940.

Oct. 14th. Lighting for Safety and Production. Joint Meeting with Institution of Production Engineers and Home Office Factory Department.

Nov. 11th. Informal Luncheon.

Dec. 9th. A Paper on **The Romance of Illuminating Engineering,** by MR. F. S. ETTE.

1941.

Feb. 10th. A Paper on **Gas Lighting,** by MR. F. C. SMITH.

Mar. 10th. A Paper on **Light and the Eye,** by DR. J. WELLWOOD-FERGUSON.

NORTH-WESTERN AREA LOCAL CENTRE.

(*Hon. Secretary:* A. H. OWEN, 11, Albert Sq., Manchester.)

Unless otherwise announced Meetings will be held in the College of Technology, Manchester.

1940.

Oct. 17th. An Address entitled **Wartime Industrial Lighting,** by MR. R. MAXTED.

Nov. 14th. A Paper entitled **Scientific Control in the Electric Lamp Industry,** by MR. J. N. ALDINGTON.

Dec. 12th. Subject to be announced.

1941.

Jan. 16th. A Paper entitled **Mercury Vapour Lamp Development—The Tubular Fluorescent Lamp,** by MR. H. R. RUFF.

Feb. ——. Subject to be announced.

Mar. 13th. A Paper entitled **The Physics of Lighting,** by MR. F. C. SMITH.

MIDLAND AREA LOCAL CENTRE.

(*Hon. Secretary:* C. J. ALLDRIDGE, 10, Boscopel Rd., Walsall.)

Time and Place of Meetings to be announced.

1940.

Sept. 13th. An Address by DR. W. M. HAMPTON.

Oct. 11th. An Address on **Industrial Lighting and the Black-out,** by MR. R. MAXTED.

Nov. 15th. Demonstrations of Lighting Equipment and Notes on Problems.

1941.

Feb. 14th. An Address by MR. L. G. APPLEBEE.

Mar. 14th. Subject to be announced.

LOCAL CENTRE FOR SCOTLAND.

(*Hon. Secretary:* M. W. HIME, E.I.M.A. Lighting Service Bureau of Scotland, 29, St. Vincent Place, Glasgow, C.1.)

Unless otherwise announced Meetings will be held at "The Gordon," 19, Gordon Street, Glasgow.

1940.

Oct. 16th. Discussion on **Industrial Lighting in War Time.**

Dec. 18th. Address by THE PRESIDENT.

1941.

Feb. 19th. Discussion on **A.R.P. Lighting and the Lighting Restrictions Order.**

NOTTINGHAM LOCAL SUB-CENTRE.

(*Hon. Secretary:* C. S. CAUNT, 62, Thackeray's Lane, Woodthorpe, Nottingham.)

Unless otherwise announced Meetings will be held in the Lecture Theatre of the City of Nottingham Gas Department, Parliament Street, Nottingham, at **6** *for* **6.30 p.m.**

1940.

Sept. 27th. An Address on **The Nature of Light,** by PROFESSOR H. COTTON.

Nov. 29th. A Paper on **The Photometric Properties of Luminescent Materials,*** by DR. W. E. HARPER, MISS MARGARET B. ROBINSON and MR. J. N. BOWTELL.

1941.

Jan. 31st. An Address on **Industrial Lighting and the Black-out,** by MR. R. MAXTED.

Mar. 28th. An Address on **The Physics of Lighting,** by MR. F. C. SMITH.

* Previously read in London on April 9th, 1940.

Local Sub-Centre in Coventry

At a meeting held at the Coventry Corporation Electricity Showrooms on September 9, over which Mr. H. Long presided, it was resolved to form a Local Sub-Centre, and a committee was appointed, with Mr. F. C. Dain as chairman and Mr. J. W. Dainty (11, Butts-lane, Allesley, Coventry) as hon-secretary. Addresses will be given by the Chairman on October 14, and by Dr. W. M. Hampton on November 11. Subsequent meetings on February 10 and March 10 are to be devoted to Industrial Lighting and Problems in Illuminating Engineering.

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THE CARBON ARC AS A STANDARD OF LIGHT

Presidential Address by

Professor J. T. MacGREGOR-MORRIS, D.Sc.(Eng.), M.I.E.E., F.I.E.S.

(Presented at the Meeting of the Illuminating Engineering Society, held on Tuesday, October 8th, 1940, at the Royal Institution.)

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I. GENERAL INTRODUCTION.

Exceptional opportunities for the more active prosecution of research on the Carbon Arc as a Standard of Light having recently been placed at my disposal through the generosity of the Leverhulme Trustees, I propose to devote my address to one section of this work, i.e., to the study of the phenomenon of the rotating comma which appears under certain conditions on the positive crater of the carbon arc.

One of our past Presidents, Mr. A. P. Trotter, to whose pioneering work especially, our profession owes so much, has devoted much time to the study of the carbon arc as a standard. I believe he undertook the research at the suggestion of the first President of our Society, Professor S. P. Thompson. Some forty-eight years ago, during the course of his work, Mr. Trotter discovered the puzzling phenomenon of the bright rotating comma when examining photometrically the positive crater of the carbon arc. It was chiefly on account of the persistence of this strange phenomenon with so-called silent arcs that this form of standard of light was more or less abandoned.

For over thirty years I have felt that, given sufficient time and resources, a standard of light could be developed using the positive crater of the carbon arc. In order that this confidence should rest on sure foundations, it was necessary to determine the conditions under which the phenomenon of the rotating comma occurs, and to evaluate its influence—if any—on the operation of the standard. The address gives an account of this work, preceded by an historical summary of work bearing on the subject of the Carbon Arc as a Standard of Light.

II. HISTORICAL SUMMARY OF WORK ON THE CARBON ARC, WITH SPECIAL REFERENCE TO ITS USE AS A STANDARD OF LIGHT*.

1808 *Davy* (1) described his discovery of the Electric Arc to the Royal Society and later gave it its name by describing it as "an ascending arch of light."

1867 *Edlund* (2) deduced a formula for the resistance (R) of the arc in terms of its length l:— $R = a + b\,l$ where a and b are constants.

1879 *Rosetti* (3) showed that the crater temperature was constant.

1881 *Abney* (4) suggested that the light emitted by a crater of constant temperature could be used as a standard of light, and (5) in a paper, "The Report on the Action of Light on Water Colours," states: "The proportion of blue rays in sunlight near midday in May is very nearly the same as the standard light (the white hot crater in the positive carbon pole of the electric arc)."

1889 *Thompson* (6) remarked: "The researches of Capt. Abney have shown that the white

* The numbers in parentheses appearing after names are references to the Bibliography at the end of the paper.

light of the incandescent surface of the crater at the positive pole of the arc is always of precisely the same composition in respect of the relative proportion of waves of different colours. This most important observation indicates beyond doubt that the temperature of the light emitting surface is always the same—this temperature being the temperature of volatilisation of carbon."

1892 *Trotter* (7) made measurements on the brightness of the crater and gave the result:—

Brightness = 42,600 candles per sq. in. at 51 volts and 26 amperes
= 64 candles per sq. mm.

In a discussion following Trotter's paper, J. Swinburne mentioned the use of the crater as a standard of light, a pinhole stop of known dimensions being suggested: while S. P. Thompson suggested, "in view of the unchanging quality of the light of the crater . . . is it not worth while . . . to adopt as a unit of light the light emitted by a sq. millimetre of crater?"

1893 *Swinburne* and *Thompson* (8 and 9) consequently attempted to use the arc as a light standard.

1893 *Violle* (10) stated that the brightness of the crater was independent of current and voltage.

1893 *Blondel* (11) modified this statement by saying that the average illumination was constant but that small, rapid variations from the mean occurred, due either to variations in the phenomenon of volatilisation or to a flame which rises up in front of the crater. The following table is due to Blondel:

Carbon.	*Intrinsic brilliancy.* Bougies decimales/sq. mm
Hard homogeneous	163.0–138.4
Cored	138.0
Cored High Voltage	134.0
Cored Low Voltage	132.0–117.2

1894 *Trotter* (12), in an investigation of the hissing arc, noticed that the crater appeared to consist of a bright line or "comma" which rotated at above 450 per second. This rotation also existed in non-hissing arcs at about 100 revolutions per second; and the direction of rotation was sometimes changed by the sweeping round of the tail of the "comma." With long arcs the "comma" became a mere flicker, and was difficult to distinguish. Six kinds of solid carbons were used, and the maximum brightness of the "comma" was 170 candles per sq. mm. Most of Mr. Trotter's investigations were made with the horizontal arc.

1897 *Claude* (13), assuming that the temperature of the arc was that of the ebullition of carbon, argued that a pressure increase meant an increase in arc temperature.

1897 *Blondel, Görges, Fleming*, and *Burnie* (14, 15, 16, and 17) showed that in an alternating arc the light emitted followed the fluctuations of the current supplying it, and that such fluctuations were due to temperature changes and not changes of crater area.

1900 *Petavel* (18), working on the arc as a standard of light, experimented with a four-electrode arc with three negatives arranged in pyramid form. His intrinsic brilliancy figures varied from 130-160 candle per sq. mm., and he showed that the light emitted was not independent of current density.

1900 *Duddell* (19) showed that pulsations of $\frac{1}{10{,}000}$ of the steady current flowing through the arc were sufficient to cause the production of sound waves. He also showed that, besides the rotation of humming arcs and the variation of current, the light and the P.D. vary with the same frequency.

1902 *Mrs. Ayrton* (20) produced the formula:—

$$E = a + bl + \frac{c + dl}{I}$$

Where E = voltage across the arc.
I = current through the arc.
l = arc length (apparent).

1902 *Blondel* and *Rey* (21) published the following results for carbons of various diameters working between 25 and 300 amperes:—

(i) Intrinsic brilliancy per sq. mm. increases with the current density in the positive carbon.

(ii) Current density varies inversely as the square root of the diameter (density $\propto 1/\sqrt{D}$) provided that the crater temperature is the same for the various carbons.

(iii) The current density/intrinsic brilliancy curve is a parabola.

(iv) The empirical value of the crater area

in sq. mm. is $0.2I^{3/2}$ where I is the current in amperes.

1904 *Waidner* and *Burgess* (22) investigated the temperature of the crater.

1907 *Blondel* (23) attempted to explain the "increase of brightness of the crater with increasing current" by stating that the electro-vaporisation point was different from the ionisation phenomena.

1910 *Rasch* (24) pointed out that, if the length of arc were taken as the distance from the bottom of the positive crater to the tip of the negative electrode instead of from the level of the outside rim of crater to the negative as Mrs. Ayrton had taken, the constant c in her equation disappears; the equation thus becomes

$$E = a + bl + dl/I$$

1913 *Forrest* (25) examined experimentally several methods of obtaining a clear view of the positive crater. Amongst them were tubular negative carbons, mechanically spun and magnetically spun arcs, and concentric positive and negative carbons; but the final arrangement was a three-electrode arc, in which the electrodes were arranged in a Y formation (all contained in a horizontal plane), one being positive and the other two negative. Each negative made an angle of 100 deg. with the positive. A nickel diaphragm with a 1 mm. hole was placed 15 mm. away from the crater. The beam of light thus obtained was photometered against a standardised metal filament lamp. The results showed that the intrinsic brilliancy was constant over a range of 6 to 10 amperes. In later unpublished work by Forrest, using a stop measured by the N.P.L., the intrinsic brilliancy was found to be between 172 and 174 candles per sq. mm. Forrest's description of the magnified image of the positive crater is as follows: "The crater is mottled, there being a large number of irregular areas which are brighter than the background. . . . The edges of any minute cracks are always the source of a bright area. . . . Everywhere over the crater, but particularly near the edges, tiny black spots can be seen which appear and disappear with great rapidity. These may be impurities, or, it is just possible, bubbles of liquid carbon."

1914 *Lummer* (26) studied—both photometrically and pyrometrically—arcs between soot carbons and between graphite electrodes at various pressures. At 0.1 atmos. the temperature of the arc fell from 4,200°K to 3,940°K, the intrinsic brightness being only 0.59 of that at atmospheric pressure. At a pressure of 25 atmos. a temperature of 5,500°K was obtained. In addition, a detailed study was made of the appearance of the positive crater, and a number of photographs are included in his book.

1915 *Duffield* (27) investigated the rate of consumption of the carbon with current and with arc length; and also he showed that the consumption-current and candle power-current graphs were approximately linear, the latter pointing to the origin, but not the former. It thus appeared that some carbon had to be consumed before any of its energy could be converted into light radiations.

1920 *Paterson, Walsh, Taylor,* and *Barnett* (28) gave the following facts on the subject of the carbon arc:—

(i) Provided the current was kept constant, large changes in voltage and arc length within the normal range of working produced no sensible alteration in average candle power.

(ii) The maximum candle power in any direction not obscured by the negative was greater the shorter the arc length for the same currents. The carbons used were positive 20 mm. to 38 mm. and negative 9 mm. and it was shown that to obtain a certain illumination from the positive it was only necessary to adjust the current; arc length and voltage across the arc being immaterial. The following law was given for the value of candle power per ampere of an axial arc:—

$$\text{C.P./amp.} = 150 - 5\frac{A}{I} - \frac{2000}{I}$$

where I = current and A = crater area, the current range being 40 amps, to 400 amps.

Intrinsic brilliancy figures varied from 156 to 178 C.P./sq. mm.

1921 and 1923 *Allen* (29) made measurements of the crater area of 6 mm. electra solid carbons, and later of

10 mm. solid carbons, in the latter case inclining the negatives upwards towards the positive so as to employ heavier currents. He obtained the following results:—

(i) Crater area is directly proportional to current.

(ii) For 6 mm. carbons current density in the positive crater is 0.746 amps. per sq. mm., whilst for 10 mm. carbons the current density is 0.442 amps. per sq. mm.

1922 *Günther-Schulze* (30) investigated the size of the cathode spot by means of a magnified image. His result showed that when the anode was so far removed from the cathode that its rays did not affect the cathode spot, the size of the spot was proportional to the current. The constant current density was 470 amps./sq. cm., from 1.5 to 10 amps.

1924 *Kohn* and *Guckel* (31) covered a large field in connection with the carbon arc, including work on the brightness of the crater. It was shown that the intrinsic brightness was constant over a large current range (5 amps. to 60 amps.) and further that the intrinsic brightness of the negative was constant above about 40 amperes, and had the same value as the positive. Experiments were performed with the arc running in various gases (air, CO_2, N_2 and argon) and at different pressures. It was found that as pressure increased the intrinsic brilliancy increased, but for the same pressure in different gases the intrinsic brilliancy had the same value. In other words, the intrinsic brilliancy was dependent on the pressure of the surrounding gas, but independent of the nature of that gas.

1926 *Rey* (32) was working on searchlight carbons of 16 mm. diameter positive and 13 mm. negative at a current of 150A. He found four distinct zones of intensity in the crater whose brightness increased from the edge to the middle, the figures being:—

Bougies/sq. mm.			
Central zone		539	Mean value = 296.5 bougies/sq. mm. (=274 candles/sq. mm.)
1st	„	463	
2nd	„	320	
Outside	„	175	

The central zone had a diameter 3.25 mm., the whole crater being 13 mm. diameter.

Using cored carbons at 200 amperes, five zones were obtained: —

Bougies/sq. mm.			
Central zone		887	Mean value = 458 bougies/sq. mm. (= 423 candles/sq. mm.)
1st	„	787	
2nd	„	605	
3rd	„	423	
Outside	„	253	

1926 *Nottingham* (33) showed that the characteristic curves depend on the absolute temperature of the anode.

1927 *Seeliger* and *Schmick* (34) made experiments for a constant current on the arc at different pressures, and showed that the kathode spot increased with decreasing pressure and the temperature of the kathode surface at the spot was lowered.

1927 *Fox* (35). An account of five years' work on the relation of C.P. per amp. of the positive crater of soot carbon arcs for various makes of electrode. The result of a prolonged investigation appeared to show that when an average of a number of readings was taken a precision of 1 part in a 1,000 could be obtained in visual photometric comparisons of the C.P. of the positive crater of two soot carbon arcs of the three-electrode type, when run in series. Measurements were made of crater areas and rate of carbon consumption; and "snapshots" of the burning crater, and in addition photomicrographs of the end of the positive crater after it had cooled down were taken. He also showed (i) that the C.P. emitted by the crater of the Y carbon arc is dependent on both the positive and negative carbons, and (ii) the positive crater area and rate of consumption of the positive carbon are only dependent on the positive carbon, i.e., unaffected by change of brand of negative carbon. (iii) That the C.P. per ampere for different diameter carbons of the same brand and mixture is of the form

$$\text{C.P./amp.} = \text{K.D.} + K_1$$

D = diameter of + ve in mm. where for Kinomarke Noris E.A. K = 4.75 and K_1 = 206.

1933 *Salway* (36). An extension of Dr. Fox's work, but it includes, in addition, measurements on Siemens-Plania A and Siemens' Plania E electrode and pure Acheson graphite electrodes. The investigation showed:

that if soot carbons are used the illumination can be specified, but the carbons cannot; whilst for graphite electrodes the reverse is the case, the electrodes can be specified but the illumination cannot. It was further shown that the C.P. per ampere was materially affected by the mass of the collar used for holding the electrodes in the case of graphite. Results were obtained for a graphite electrode externally heated so as to reduce the heat flow back along the electrode. For the same reason a graphite tip was mounted on a soot carbon base and the alteration in the C.P. per ampere observed.

1933 *Jones* (37). "A spectroscopic examination of arcs between plain soot carbons of various degrees of purity being an attempt to correlate the spectra with C.P./amp. of the positive crater."

1935 *Clark* (38). In this work measurements of the response of a photovoltaic cell were made alternately, first when exposed to the arc screened by a suitable yellow filter, and secondly to a suitably adjusted tungsten filament lamp. He challenged the work of previous investigators and demonstrated that, though the C.P./ampere and the crater area-ampere graphs were straight lines, they did not pass through the origin but cut the ampere line at between 1.5 and 2.5 amps. when 10 mm. electrodes were used. Work was done on graphite as well as Siemens-Plania electrodes studying how the brightness varied over the face of the crater, as well as its variation with time at any given point.

1935 *Chaney, Hamister,* and *Glass* (39) reviewed the entire field bearing on the properties of carbon at arc temperatures and submitted new experimental data. Results indicate that (i) carbon sublimes without melting at ordinary atmospheric pressure; (ii) the temperature of the positive crater approaches a limiting constant value; (iii) the maximum "brightness" temperature of the carbon (Acheson graphite) crater is 3810 degrees K; (iv) the wavelength of maximum radiation intensity lies between 0.735 and 0.740 mm.; (v) the probable true crater temperature lies between 3925 degrees and 3970 degrees K. The preferred conditions for insuring maximum crater brightness are as follows: spectroscopically pure graphite for positive electrodes preferably less than 6 mm diams., crater diam. 3.5 mms. or less, in a right-angled arc having a soot carbon for the negative. For a 6 mm. positive and a 3 mm. negative the loading being 10 and 14 amps.

1938 *Krijgsman* (40) measured the *total* emission in ergs per cub. cm. per sec. of the positive crater of a carbon arc in air for different wavelengths using 8 mms. positive and 6 mms. negative Siemens-Plania A solid carbons in a right-angled arc at 10.2 amps. on a 440 volt d.c. circuit. He found that when a correction was made in the ultra-violet region to eliminate the effects of gas emission that the crater of the right-angled arc could be used as an absolute standardised source of total radiation, having an emission equal to that of a black body at a temperature of about 3800 degrees K. It is claimed that as a standard of total emission it gives a constancy within 2 per cent. when all the precautions stated are taken.

1940 *MacPherson* (41) made the following measurements on carbon arcs, using as positive ½-in. pure graphite and 5-16-in. spectroscopically pure soot carbon, and as negative 3-16-in. spectroscopically pure soot carbon, in a right-angle arc with currents of 10-12.5 amps. The following results were obtained:—

	½" Graphite.	5/16" Carbon.
Distribution Temperature	3860°K	3840°K
Colour Temperature	3990°K	3855°K*
Brightness Temperature	3820°K	3680°K†
Max. True Temperature	3995°K	3845°K
Emissivity	0.77	0.78

He showed also that, but for the effect of the cyanogen bands, the carbon arc radiation may be regarded as that from a black body.

III. INTRODUCTION

The complete examination of all the factors affecting the C.P. emitted by the positive crater of a carbon arc is naturally a lengthy business. The work falls into a number of separate sections.

The remaining portion of this paper is devoted to one section only, i.e., the examination of the rotating

* A diaphram having a 2.5 mm. diam. hole was placed about 4. cm. in front of the graphite arc and one of 3.75 mm. for the soot carbon arc.

† Uncertainty of about 15° due to difficulty of extrapolating this temperature from primary standards. The actual arc brightness temperature is believed to be reproducible to within 10°K. (This is to within 1.5 per cent in light.)

comma and its effect on the accuracy of the standard.

When a hand-fed d.c. arc is struck in the normal way, the well-known noisy hissing occurs due to excessive current and the shortness of the arc. As its length is increased it finally settles down into the silent state.

Between these two states, as the arc is lengthened, it emits a more or less musical note whose frequency steadily decreases until it merges into the silent arc.

In her work on the electric arc, Mrs. Ayrton refers to this humming as distinct from the normal hissing arc. She deals first with two kinds of hissing, and states:—

> "There is a third sound rather like the wind blowing through a crack, which comes just before the hissing with big currents begins. It is a sound very difficult to maintain, for the arc has a great tendency at that particular stage to become either hissing or silent."

Mr. A. P. Trotter, in 1894, while on work connected with the use of the arc as a standard of light, discovered that, when the arc is humming, a radical change in the appearance of the positive crater takes place. To reduce the light emitted by the arc for photometric comparison purposes, he used a rotating slotted disc. During the course of these experiments, Trotter noticed peculiar shadows cast on the wall, and decided to investigate the crater stroboscopically. For this purpose he used a lens to produce an enlarged image of the crater, and interposed a slotted disc driven by a variable speed motor.

The result of this examination was the discovery of a rotating comma-like appearance which occurs when the arc is humming. By means of a pair of telephones he also found that, superimposed on the main arc current (d.c.), was an a.c. component which was related to the humming of the arc.

I would like to suggest that this phenomenon be known as the "Trotter comma," as a tribute to Mr. A. P. Trotter's pioneer work in this field. He hoped to investigate this phenomenon more fully, but unfortunately was unable to do so, and little work has been done on it since that time.

During the present work on the arc as a standard of light, using the Forrest three-electrode arc, it has been found that to obtain a crater which is steady and well defined it is desirable to load the positive as heavily as is consistent with silent operation. This is in accord with the observations of Chaney, Hamister, and Glass, and others, on the two-electrode right-angled arc. Low values of the current in the three-electrode arc produce a crater whose edges are not well defined and which tends to "flop" bodily up and down the face of the positive. The reason for this seems to be that the crater is unable to fill the entire end of the carbon for low values of the current.

For the reasons given above, it is necessary for stability of operation to use the arc in such a condition that the maximum possible current is being carried. As the rotating comma appears only at higher currents, it became necessary to continue the work which Trotter had started, and attempt either to eliminate the humming period between the silent and the hissing arc, or to determine its photometric incidence.

IV. OBJECT OF THE PRESENT RESEARCH.

The object of the present research was to determine:—

(1) The cause of the rotating comma,

(2) The possibility of increasing the loading of the positive without causing the incidence of humming. Or failing this,

(3) The possibility of using a humming arc as a standard of light, and so increasing the range of arc lengths over which measurements of candle power could be made.

V. THE COMMA AND EFFECTS ASSOCIATED WITH IT.

General.

Trotter, in the discussion following Duddell's paper (J.I.E.E. v. 30, p. 272-4, 1900-1901), with remarkable foresight, suggested that any paper on the Humming arc should contain "Photographs of the white spot, the Comma, and the Butterfly, and an investigation of the relation between periodicity of hum, current, and length of arc."

Section 1. Examination of Positive Crater, Negative Tip, and Arc Stream.

(a) *Visual Examination*

When examining the comma phenomenon in the axial arc, owing to the impossibility of viewing the positive crater or negative tip normally, only oblique views can be obtained of either electrode. The comma can most readily be seen with a displaced electrode; but from views obtained by this arrangement it is difficult to determine what the phenomenon would be like in the perfectly axial arc.

A few salient points, however, may be noted. There is a bright patch on the positive which has been

called comma-shaped, but on closer investigation it appears to be of a sector shape, having displacements against the direction of rotation which are the greater as one passes from the centre to the circumference; and the angle of the sector is between 60° and 90°. Whether the comma spins on the point of the sector or at a point slightly inside it is open to question.

The shape of the negative patch is different, for in this case it is formed on the more or less pointed electrode, while the positive comma is within the crater. If the negative has not attained its final form —being too rounded—then the negative patch appears as a bright, slightly mobile, circular area moving over the face of the negative and at any moment only occupying half of the whole area swept out. When the negative is more pointed, then the patch spreads round the sides so that, when looked at along the direction of the arc stream, it would probably appear as a circle pivoted eccentrically.

The arc stream joining these two bright portions has one edge roughly perpendicular to the surface of the crater and centred in it. The outer edge is bowed outwards. The colour of the flame is a purple blue.

(b) *Photographic Examination of the Comma and Current Ripple.*

An image of the positive crater was projected through a stroboscopic disc on to a screen at a distance. The attached photographs (Fig. 1) give some idea of the appearance. (Experiment.)

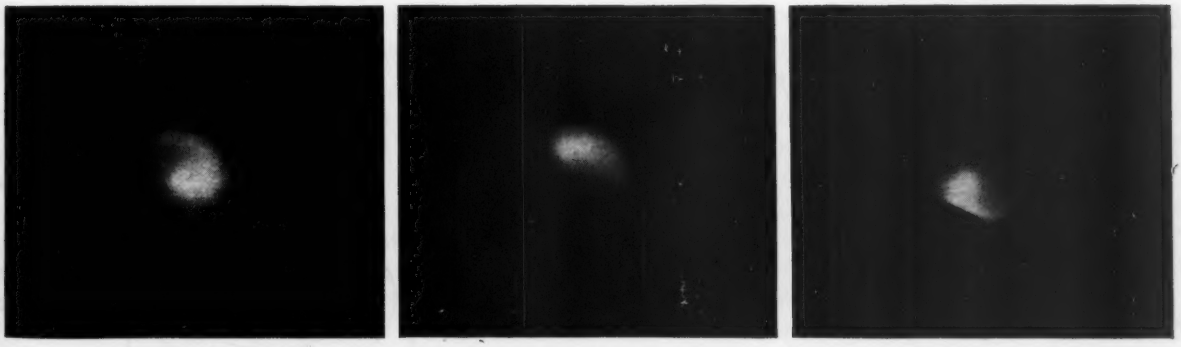
At rare intervals a figure was seen on the screen resembling a butterfly and moving quite as erratically, but it was far too fleeting for photographs to be secured.

Simultaneously with the rotating comma there is an audible hum produced by the arc (Experiment) and there is an a.c. ripple in the d.c. arc current, whose magnitude was generally of the order of one $\frac{1}{2000}$th of the arc current, though occasionally it might attain $\frac{1}{500}$th. (Experiment.)

Trotter proved the identity of frequency of the a.c. ripple and the hum by comparing the note heard in telephones, shunted across the main ballast resistance, with the hum of the arc.

In the present work the identity of frequency of rotation of the comma and the current variations has been proved in the following way. An image of the crater of the arc was projected on to a screen beside a cathode ray oscillograph. The a.c. component of the arc was applied to the deflecting plates of the C.R.O., the projected image on the screen and the oscillograph trace being observed simultaneously through a stroboscopic disc. When the arc length was adjusted so that the comma appeared stationary, the trace on the oscillograph was also stationary. This is as would be expected if the frequency of rotation of the comma were identical or a multiple of the frequency of the a.c. ripple. (Experiment.)

Oscillograms of the wave form of the current a.c. ripple were made by examining the potential drop across the ballast resistance of the arc by means of the C.R.O. Oscillograms are given (Fig. 2) for different multiples of 25~. The arc was given 10 to 15 minutes to attain its stable form. In general, as the current was decreased the higher harmonics became more pronounced. The wave form at low currents



4 exposures, each 1/5th cycle. Displaced axial 10 amp. arc.—Frequency about 150 cycles.

1 or 2 exposures, each 1/5th cycle.

Right-angled 10 amp. arc. Frequency about 150 cycles. 1 or 2 exposures, each 1/20th of a cycle.

Fig. 1. Photographic reproduction of comma characteristic of rotating arc.
Note:—Negative slightly obscures crater in two photos.

changed so rapidly that it was impossible to obtain reasonable photographs. (Oscillograms.)

Further experiments on perfectly symmetrical axial arcs and arcs in which the positive electrode was shifted parallel with itself appear to show that the prime cause of the effects observed in a d.c. humming arc is the rotation of the current carrying arc stream around the surface of the end of the positive electrode. The other effects, audible hum, and a.c. component of the arc current being dependent upon this rotation and upon the actual geometric form of the arc.

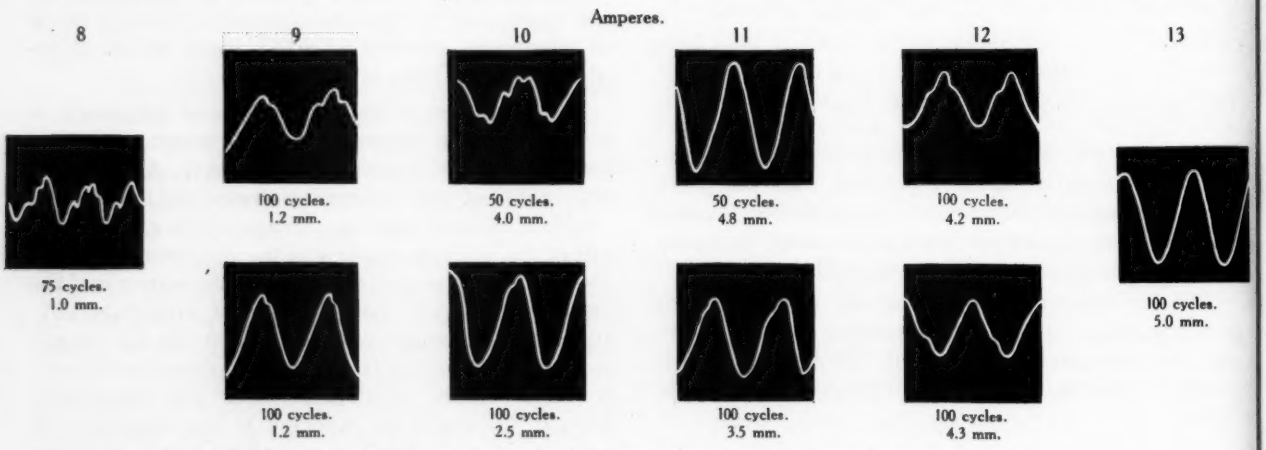


Fig. 2. C.R. Oscillograms of arc current pulsations for currents from 8 to 13 amperes for an axial arc S.P. electrodes.

Section 2. Variation of Apparent Brightness over the Surface of the Positive Crater.

An examination of the brightness of the projected image of the positive crater of an inclined axial arc (Fig. 3) was made by means of a photo-electric cell, having a pinhole diaphragm. The arc was between 10 mm. Siemens-Plania A carbons running at 11 amps. So as to obtain a fuller view of the positive crater on the screen, the positive electrode was withdrawn about 3 mm. In this way the minor axis of the ellipse was considerably increased.

The measurements were made at the centre, on an ellipse $\frac{1}{3}$ of the radius out (suffix 1) and on an ellipse $\frac{2}{3}$ of the radius out (suffix 2). (Fig. 4.)

Using the convention North, South, East, and West, the following results were obtained. (See Fig. 5.) It will be seen, measurements were also made introducing a coloured screen between the arc and its projected image with the object of reducing very largely the violet and ultra-violet response.

Each ordinate in the graph (Fig. 5) represents the average of two readings.

These results show that the greatest response is for the position S_2 and next for N_2. Further experiment is required before a complete explanation of these figures can be given.

The above experiments relate to the average

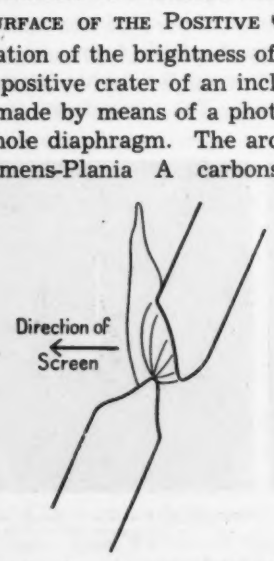


Fig. 3. Diagram of Arc: Side View.

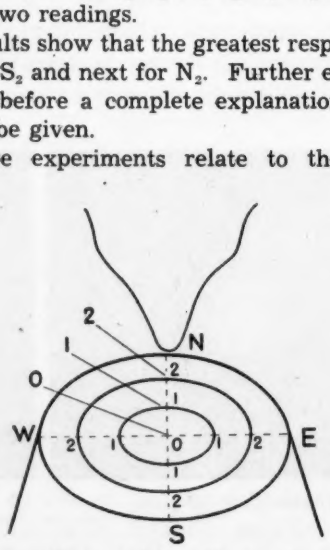


Fig. 4. Diagram of Arc: Showing Crater.

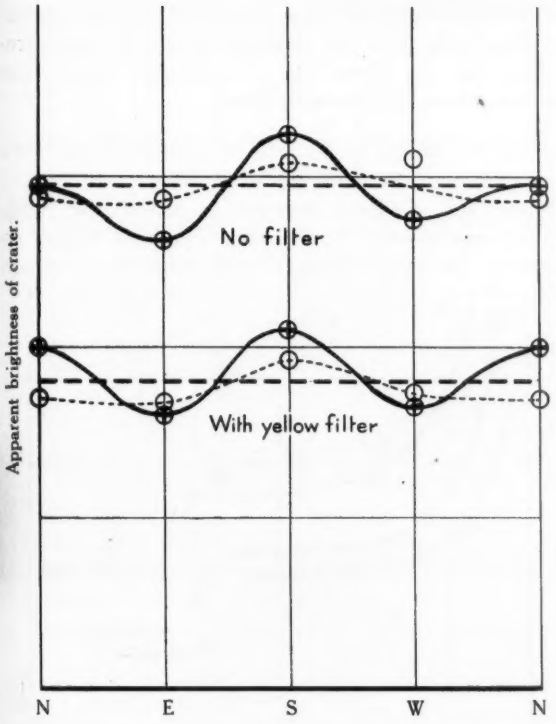


Fig. 5.

brightness of any spot on the crater. To obtain, however, the instantaneous variation of brightness, the photo-electric cell was connected through an amplifier to a C.R.O. (Experiment.)

An examination of the patterns obtained reveal, firstly, that the centre of the crater remains constant in brightness, and, secondly, at any point away from the centre of the crater, the oscillograph indicates that the angular width of the bright part of the comma is very approximately a right-angle.

Section 3. Relation of Current Arc Length and Frequency of Hum.

This section describes experiments on these relations. Great attention was paid to the accurate maintenance of the length.

As Mrs. Ayrton has shown, on altering the current the final form is not reached until fifteen minutes have elapsed (much more if the change of current has been large), so special attention has been given to this matter.

In this address the length of the arc is taken (not the *apparent* length, which is the gap shown by the projected image, as Mrs. Ayrton did), but the *true* length, which, as Rasch pointed out, is the distance separating the tip of the negative from the bottom of the positive crater, a length which is greater than the apparent length by the depth of the crater cup. (See Table I.).

TABLE I.

Current.	*Frequency.*	*True Length.*	*Correction.*
8A	50	2.3	0.7 mm.
9A	50	3.0	0.2
	100	1.9	0.5
10A	50	3.05	0.5
11A	50	3.95	0.2
	100	2.05	0.4
	150	1.35	0.5
	200	.90	0.6
	75	3.5	0.3
	125	2.3	0.5
12A	50	5.8	0.15
13A	100	4.20	0.1

The true length was determined by adding to the amount as determined by the projected image, a quantity measured mechanically from the depth of the crater.

The probable accuracy in these measurements is about 5 per cent.

A Cossor double-beam Cathode Ray Oscillograph was used for measuring the frequency and amplitude of the electrical pulsations. The frequency was measured in terms of the 50 ~ mains; these measurements can probably be relied on to 1 per cent.

The method adopted was to burn the arc at a fixed current and adjust its length until a multiple of 25 ~ was obtained as indicated by the C.R.O. Keeping the current constant, the length was then continuously adjusted, so that the pattern on the C.R.O. was kept as stationary as possible for ten to fifteen minutes. At the end of this time the electrode tips had practically assumed their final form for these particular conditions.

In the measurements great care was taken to ensure that the arc was vertical and that the electrodes were not laterally displaced.

The arc length for 50 ~ and 100 ~, and for the "Humming-Hissing" transition was measured for different currents, as also the lengths for different frequencies at 11 amps.

The results are set out in Figs. 6 and 7. Fig. 6 shows that as the current rises it is necessary to increase the arc length to keep the frequency constant. Fig. 7 shows that the relation between

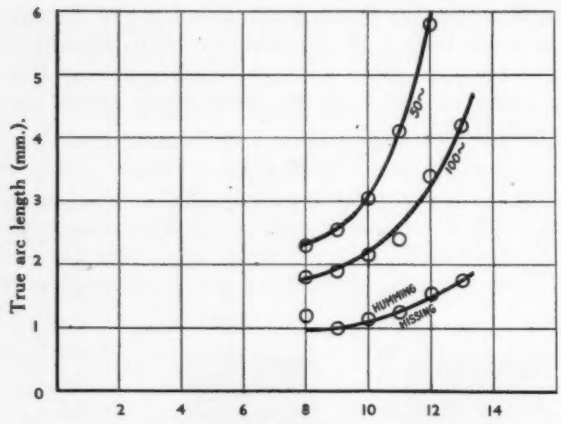


Fig. 6. Current (amperes).

frequency and length at constant current is given by

$$\frac{1}{L} - \frac{1}{L_0} = k\,f$$

L=arc length, f=frequency, k=constant, L_0 is a constant representing the arc length at zero frequency.

The result of the foregoing experiments brings out the interesting fact that the well-known volt ampere characteristics for different lengths (Fig. 8) may be

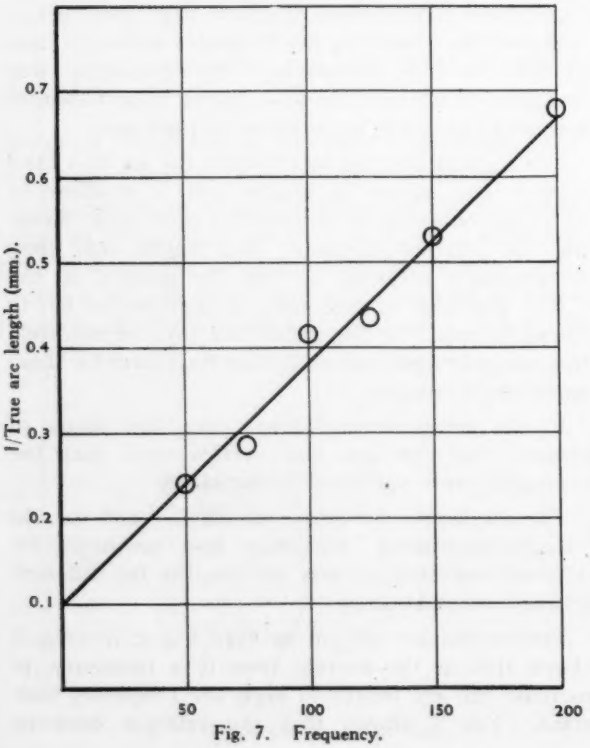


Fig. 7. Frequency.

divided into three portions instead of two, the Silent, the Humming, and the Hissing. Lines of equal frequency for the Humming are seen to spread out fanwise across the characteristics.

Section 4. Effect of Change of Circuit Constants Upon Frequency of Hum.

Since the rotating comma is associated with electric oscillations in the arc circuit, it might be expected that alterations of the resistance, induct-

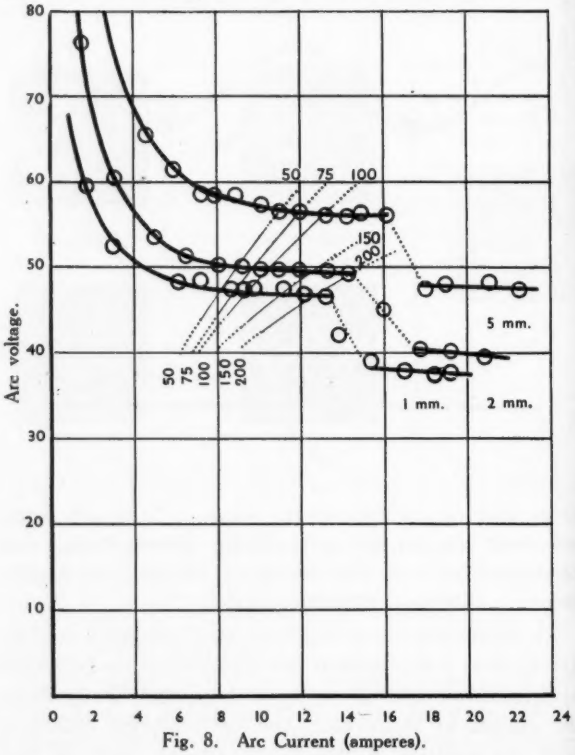


Fig. 8. Arc Current (amperes).

ance, or capacitance in the circuit would alter the frequency of hum. This was tested experimentally.

(a) Effect of Resistance.

The effect of external resistance on the frequency of hum was examined by doubling the supply voltage from 120 v. to 240 v. Results shown in Fig. 9 indicate that, for constant frequency and constant current, an increase in circuit resistance (increase of overall voltage) necessitates a reduction in length. Or, looking at it from another point of view, at constant arc length, an increase in circuit resistance causes a decrease in frequency of hum.

(b) Effect of Inductance.

A heavy air-cored inductance of 30 millihenries was placed in series with the arc. The relation of

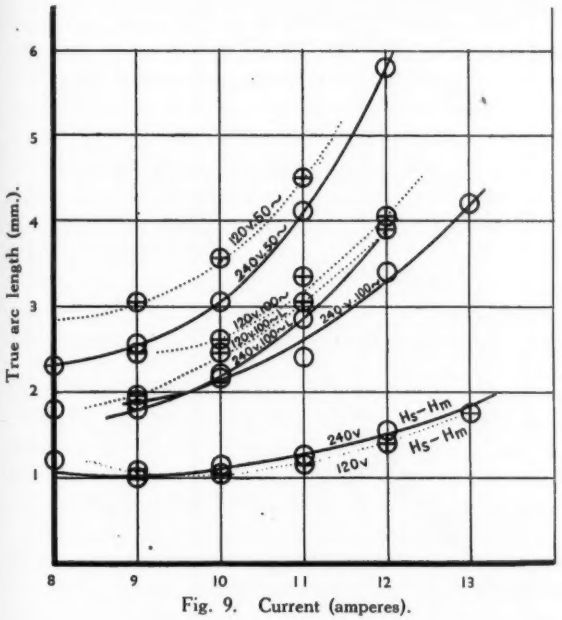


Fig. 9. Current (amperes).

arc length to current was found for the 120 v. and 240 v. supplies at 100 ~.

The singularly small change produced by the addition of this enormous inductance is surprising. The effect of inductance seems to be to reduce the effect of change of circuit voltage. The inductance reduces the amplitude of the pulsations and their associated harmonics, as would be expected.

(c) *Effect of Capacitance.*

Shunting the arc with an 8 μF condenser resulted in a reduction of the effect of change in circuit voltage as in the case of inductance.

Section 5. Effect of Change of Diameter of Positive Electrode on Transition Points.

It is well known that the hissing point of a carbon arc is related to the size of the positive electrode.

A series of measurements of the hissing-humming and humming-silent transition points were made for positive carbons of 7, 10, and 12 mm. diameter.

The results of these measurements are given below in Table II.

It appears that for low currents the apparent length of arcs for these transition points with different diameters of the positive carbon converge to the same value.

TABLE II.

7 mm. positive Electrode (S.P.Bio).

Current		8		9		10
Length	Hs—Hm	.55	...	1.10	...	2.00
	Hm—Si	1.45	...	1.90	...	3.10

10 mm. positive Electrode (S.P.A. 38).

Current		8	10	12	14
Length	Hs—Hm ...	.25	.65	1.55	2.75
	Hm—Si ...	1.35	1.85	2.85	4.35

12 mm. positive Electrode.

Current		8	10	12	14	16
Length	Hm—Si ...	—	.85	1.30	1.80	2.10
	Hs—Hm ...	1.45	2.00	2.55	3.10	—

Note.—Hs = Hissing, Hm = Humming, Si = Silent.

Section 6. Effect of External Influence.

(a) *Axial Magnetic Field.*

Electrons travelling parallel to an axial field will experience no deflecting force; those whose velocities have a component perpendicular to the field will experience a force tending to urge them into helical paths; the direction of rotation is the same for all such electrons, so that on reaching the +ve electrode they will meet the surface at an angle θ (Fig 10).

It is probable, however, that for a given current and arc length the mean velocity and direction of motion of the electrons from the cathode are fixed. Hence the effect of increasing the axial field will be to decrease the value of θ (the mean angle at which the electron strikes the +ve electrode). Consequently the force exerted by these electrons on the arc stream will be increased by the increased axial field. It would seem therefore that when an axial magnetic field is applied there should be an effect on the direction of rotation, as this is influenced by currents of

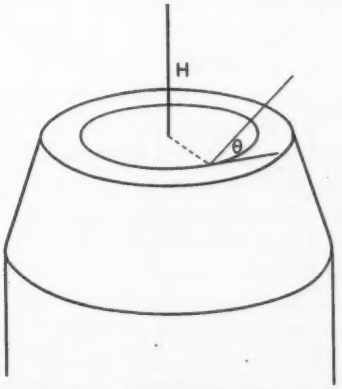


Fig. 10. Diagram of Crater showing course of arc stream.

air; and, in addition, an effect on the frequency of rotation.

The experimental arrangement used to study this effect is illustrated in Fig. 11. Two coils, A and B, having an equal number of turns, were mounted a radius apart, as in the Helmholtz Gaugain tangent galvanometer, thus giving a large volume of space in which the field is uniform. The arc was mounted vertically between the coils at their exact centre, and the frequency of rotation of the comma was observed by means of a C.R.O., while the comma itself was observed through a stroboscopic disc and arrangement of mirrors and lenses. Its direction of rotation was determined by first adjusting the speed of the motor until the image of the comma was stationary on the screen and then either increasing or decreasing the speed of the motor, while observing the direction of rotation of the image.

The results of these investigations may be summarised as follows:—

For a humming arc with no external magnetic field the effect of switching on the field is to increase the frequency of the oscillations. This increase in frequency is apparently independent of the direction of the field (the fields used were 14 and 28 gauss).

The maximum frequency of oscillation before the arc breaks from humming to hissing is increased by the field. In the case of a normal humming arc, this upper frequency is of the order of 350 ~, while for a field of 28 gauss it is raised to about 800 ~.

For an arc which has burnt until it has reached the

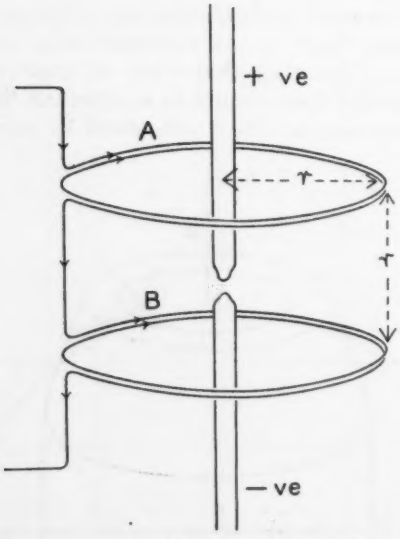


Fig. 11. Arrangement of Helmholtz Gaugain Coil to produce uniform magnetic field.

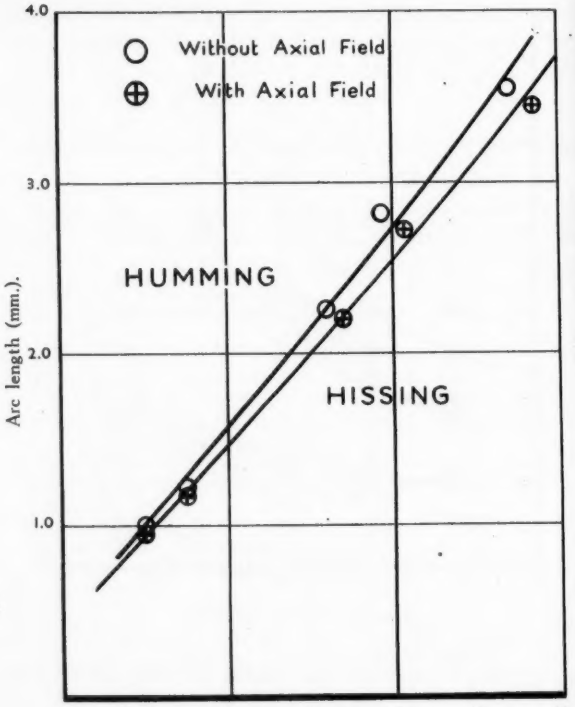


Fig. 12. Current (amperes).

silent state the axial field produces oscillations in the arc current. A stroboscopic examination of the crater shows that the comma has reappeared. Another effect noticed in this case is that if with no field the arc is so long that the crater wanders over the surface of the carbon, the field along its axis tends to prevent this wandering and pulls the crater back to its normal position. These effects also are apparently independent of the direction of the magnetic field.

A series of twenty observations made on the direction of rotation of the comma, ten for each direction of the magnetic field showed that in each case the direction of rotation is determined solely by the direction of the field. With no magnetic field there is no preferential direction of rotation of the comma, but when the magnetic field is applied the direction of rotation of the comma is that which would be expected if the magnetic field were spinning the arc stream.

Put in another way, the effect of the axial field is to cause the electrons with non-axial paths to assume helical orbits which tend to screw into the +ve electrode.

A series of measurements were made on the relation between the length and current for the transition between the hissing and the humming arc, both

with and without the axial field. Measurements on the transition between the humming and the silent arc were impossible, as with the fields used (14 and 28 gauss) the arc was never silent, although it was burnt until it was very unstable owing to its length.

These measurements are given in Fig. 12, and they show that the application of an axial field enables the arc to be burnt at a slightly higher current before hissing begins.

When running the arc in a sprouting magnetic field, as produced by using one or other of the Helmholtz coils, the results obtained were the same.

(b) *Air-jet.*

When a gentle horizontal jet of air was directed to the side of the arc stream of a silent vertical arc, pulsations in the arc current were started. On stroboscopic examination of the direction of rotation of the comma, the direction was found, in nineteen cases out of twenty, to be that which would be expected if the air-jet were whipping the arc stream around the axis of the arc. Experiments without the air-jet indicated that there was no preferred direction of spin.

Section 7. Suggestions Bearing upon Theory of Rotation Comma Effect.

In June, 1894, Mr. Trotter*, writing to Prof. Silvanus Thompson, made the following statement:—

> "If an inrush of air is otherwise than radial, a rotatory motion is started and persists, as when water running from a wash-basin moves in a vortex. In a wash-basin the water can get away, in a tornado also, the air can get upwards and outwards; but in the arc condensation due to chemical combination and lowering of the pressure must be looked for as a sink for the vapour stream."

In addition to the cause of the rotation, the effect of the bunching of the arc stream when the arc passes from the silent into the humming condition is much more difficult to explain. Possibly, it is similar to the "pinch" effect. The curving of the comma is reasonable owing to the greater velocities of the parts of the comma near the tail.

Also the following facts must be accounted for in any satisfactory theory. A rise in frequency is caused:—

(a) by an increase in current,
(b) by a decrease in length,
(c) by an axial magnetic field.

When the current and the length are maintained constant then the amplitude of current oscillations is constant to within 10 per cent.

The time average current density over the whole area of the positive crater is unaffected by the incidence of the comma.

* "Mrs. Ayrton's Electric Arc," p. 300.

Section 8. Summary.

To sum up:

(1) The rotation of the arc stream and the hum associated with it are phenomena inherent in the arc stream itself. The frequency of hum, to a close approximation, is dependent on two factors alone, i.e., the current and the length of the arc.

Minor effects are that for constant values of current and length, a doubling of the overall voltage reduces the frequency some 10 to 30 per cent. A thousandfold increase in inductance in series with the arc reduces the above change to about a half. The inclusion of a large capacitance (8 μ F) in parallel with the arc reduces this change almost to the vanishing point.

So far the influences external to the arc which have been found to alter the phenomenon are (1) that its frequency can be increased by the superposition of an axial magnetic field—the stronger the field the higher the frequency.

(2) The direction of rotation can be reversed by a jet of air applied tangentially or by the application of an axial magnetic field in the proper direction.

(3) An axial magnetic field will allow the arc to be burnt at a slightly higher current (3 per cent.) before breaking into the hissing state than without it.

VI. EFFECT OF HUM ON USE OF ARC AS A STANDARD OF LIGHT.

The foregoing experiments were undertaken, as previously stated, in connection with a study of the C.P. emitted by the positive crater of the carbon arc, with the object of ascertaining whether the Trotter rotating comma altered in any way the value of the C.P. obtained for given currents. It thus became necessary to study the laws controlling the phenomenon so as to be able to insure reliability in reproduction. Though it is obvious that these experiments require considerable extension (if an exact theory is to be formulated), sufficient work has been done to enable the experimenter to control the phenomenon. Having reached this stage it was possible to proceed with the main line of research.

A linear relation has been shown to exist between

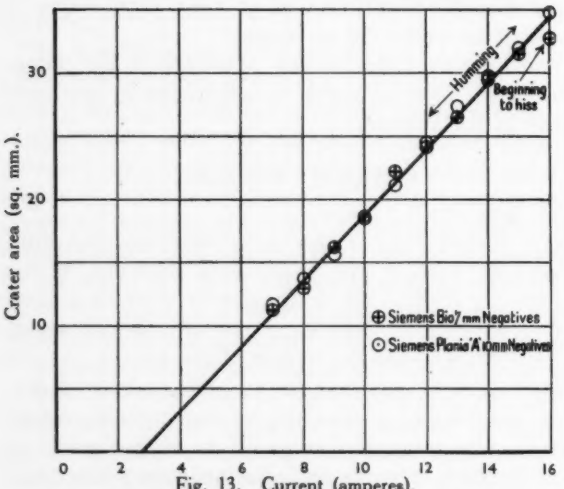


Fig. 13. Current (amperes).
3 electrode arc. Siemens-Plania 10 mm. positive.

current and crater area (Fig. 13) and between current and candle power (Fig. 14) for the silent axial arc. Experiments on the three-electrode arc were made on the same lines. These show, firstly, that this linear relation holds for the silent portion of the graph for this form of arc also. Secondly, that this linearity continues throughout the humming portion until the arc starts to hiss. Thirdly, that there is no discontinuity between the silent and the humming parts of the graph.

These experiments make clear that when the comma is present, although the current-carrying area appears to be reduced to less than a quarter of its previous value, there is no other appreciable change in the behaviour of the arc.

This result is most satisfactory from the point of view of the use of the arc as a standard of light, in that the fact that the arc hums in no wise invalidates its use for that purpose. The positive electrode may therefore be given the maximum loading at which it does not hiss.

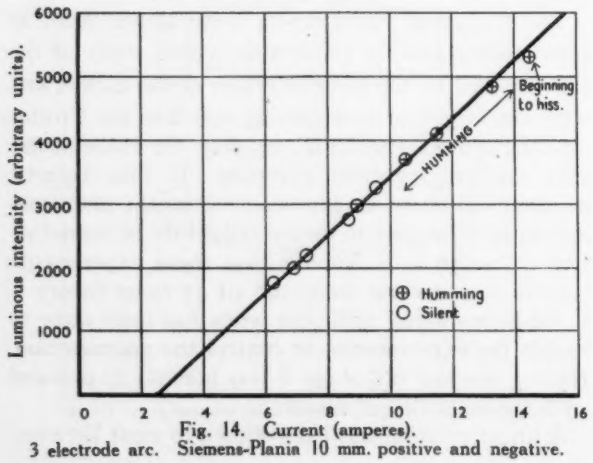


Fig. 14. Current (amperes).
3 electrode arc. Siemens-Plania 10 mm. positive and negative.

VII. ACKNOWLEDGMENTS.

First, I desire to express my grateful thanks to the Leverhulme Trustees for their assistance which has made this work at all possible. My thanks are also due to my research assistant, Mr. A. J. Beard, by whom the greater part of the experiments were carried out, and, later, to Mr. A. G. Stainsby, who followed him. The research was conducted in the Photometric Laboratory attached to the Electrical Engineering Department at Queen Mary College, and my thanks are due to Professor W. J. John for facilities thus extended to me.

To the Managers of the Royal Institution I am greatly indebted. Through their kindness, the unique facilities of their Lecture Theatre for demonstration were whole-heartedly placed at my disposal for the experimental illustrations.

In concluding I should like to take this opportunity of acknowledging the practical interest shown by Sir Lynden Macassey in this work, and also my warm appreciation of the encouragement which I have at all times received from Mr. A. P. Trotter in this quest for a high power standard of light.

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